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LASERS IN SPACE

TECHNOLOGICAL OPTIONS FOR ENHANCING US MILITARY CAPABILITIES

by

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Lasers in Space Technological Options for Enhancing US Military Capabilities

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The Author

Lieutenant Colonel Mark Rogers, USAF, a 1976 graduate of the USAF Academy where he majored in physics, has been involved in defense-oriented research and development for the past twenty years, focusing primarily on applications of lasers for military systems. His background includes test range support for future space programs and capabilities analysis for optical tracking systems while at Vandenberg AFB. After completing his MS and Ph.D. in laser/optics, he conducted and managed research on various high energy laser weapons concepts at the AF Weapons Laboratory, including coupled laser technology for space-based lasers as part of the Strategic Defense Initiative. While teaching undergraduate physics at the USAF Academy, he led a research team investigating stimulated Brillouin scattering and stimulated Raman scattering for possible use in nonlinearly coupling laser devices. He headed a laser biophysics team at the Armstrong Laboratory, where they established new safety thresholds for sub-nanosecond pulses and near infrared wavelengths as well as

studied various nonlethal technologies based on optical systems. Prior to entering the Air War College, he served as the deputy chief scientist for Armstrong Laboratory, spearheading the Lab's information warfare program and overseeing multiple basic research and scientific personnel programs. His current interests include directed energy weapons, nonlinear dynamics, and laser-tissue interactions. A 1997 graduate of the Air War College, Lt. Colonel Rogers conducted this research under the auspices of the Center. His current assignment is in the Pentagon.

Abstract

The emerging importance of space-based systems is matched by the maturing of laser technology, giving a potential synergy to enhance military capability. For example, global awareness is one of the AF goals to give the US military the competitive advantage in future conflicts. Obtaining global awareness requires a tremendous amount of information being acquired and transferred over vast distances. Space-based laser communication satellites offer the potential of greatly increased data rates, which is just one example of how lasers in space could significantly improve US military capabilities.

Recent strategic planning studies have identified various concepts for lasers in space, including both laser weapons and collateral applications such as communication and remote sensing. Four functional classes of systems (enabling, information-gathering, information-relaying, and energy delivery) serve to organize the various concepts and relate them to the new AF core competencies as well as the traditional AF roles. This study analyzes these concepts, scoring them for technical feasibility, technical maturity, operational enhancement and operational cost. The most promising concepts include space-based laser target designation, space-based battlefield illumination, laser communication, and active remote sensing for battle damage assessment and weather characterization. Several strategies can accelerate the development of space-based laser systems, such as using the new AF battlelabs and advanced technology demonstrations.

I. WHY LASERS IN SPACE?

Both laser technology and space operations have matured substantially in the recent decades, offering synergistic possibilities of using lasers from space-based platforms to improve US military capabilities. Coherent laser light offers a number of unique advantages as does the space environment, permitting speed-of-light applications such as optical communication, illumination, target designation, active remote sensing and high-energy weapons. Many of these concepts have been discussed in recent strategic studies, but it will take innovative leadership and close cooperation between researchers and operators to bring the concepts from the laboratory to the field.

One of the recent themes in US military thought has been achieving global awareness in order to establish dominant battlespace awareness. According to General Ronald Fogleman, AF Chief of Staff, "The reality is that in the first quarter of the 21st century it will become possible to find, fix or track and target anything that moves on the surface of the earth."[1] Whomever has such awareness, the theory goes, will have the upper hand in any military operation. Awareness equates to the possession of adequate information. Achieving *global* awareness will require obtaining, processing, and relaying massive amounts of information

in near-real time across vast distances. Space-based laser systems bring many unique characteristics to the battlefield, and thus represent powerful tools in achieving global awareness.

Each of the new Air Force core competencies — Air and Space Superiority, Global Attack, Rapid Global Mobility, Precision Engagement, Information Superiority, and Agile Combat Support — highlights an area of expertise for the AF in accomplishing both warfighting and military-operations-other-than-war (MOOTW) missions. As discussed more fully in a later section, lasers in space can enhance each of these competencies. (A comprehensive list of acronyms is included at the end of this report.) Space-based laser systems offer unique opportunities to help the warfighters of the AF and the other services achieve these missions.

The Department of Defense and NASA are testing various space-based laser concepts, many of which have high military utility. While some projects are good candidates for collaboration, the overall development is ad hoc. There is a clear need for more overarching coordination across the agencies and between the researchers and the warfighters. This study proposes a common framework for lasers in space, and should serve as a catalyst to further cooperative development of the more attractive concepts.

Objectives

The thesis of this study is that many emerging military requirements can be met through the use of laser systems deployed on space platforms. Laser technology has matured sufficiently in the past decade to provide highly reliable, cost-effective, energy-efficient and wavelength-flexible systems that can be applied to a variety of missions, such as remote sensing and communication. Access to space is maturing with new launch vehicles on the horizon. The unique characteristics of the space environment greatly enhance the utility of deploying lasers in space. These include the lack of any medium to attenuate the beam and the ready access to the entire global surface. This synergy of lasers in space offers the warfighter a new and vastly more competitive tool in future conflicts. However, technology developers must move aggressively to field prototypes that demonstrate the capabilities and potential of space-based laser systems for a variety of missions. The various avenues to expedite bringing the most promising concepts into fielded systems is the final focus of this report.

In an increasingly resource-constrained environment, the Air Force must successfully blend strategy and technology. One straightforward definition of strategy is "a broad concept, embracing an objective, resources, and a plan for using those resources to achieve the objective."[2] There are two relevant types of strategies. First, *acquisition strategy* applies R&D resources (funds, manpower, facilities, etc.) to develop new technologies that match operational deficiencies identified by the warfighting commands. Second, *operational strategy* examines the threats to the security and national interests of the US and its allies, matches current capabilities against the threats to achieve military objectives, and highlights areas where improvements in capabilities could enhance military success. It is at this point that the two strategies interact. The warfighter must face any conflict with the tools at hand, striving for victory with diligence and ingenuity. The military researcher must work with equal diligence and ingenuity to find new or more effective tools for achieving military objectives, which in some cases will require new technology and in others might mean

repackaging existing technology into new systems. It is increasingly important that the system developers and the operational users work closely together. One new AF attempt to generate this synergy is the concept of battle labs that are discussed at the end of this report.

Scope

The field of laser technology has greatly expanded since the laser was first demonstrated in 1960. Innovative minds have found many applications of these technologies, including active remote sensing, active imaging, optical communication, power beaming, and high-energy weapons. Since the early 1960s, the complexity of the military missions has dramatically increased, with more diverse theaters of operation, expanded spectrums of conflict, and tremendously increased requirements for information delivered in almost immediately to the warfighter. It would be impossible in a short report to comprehensively address all the unique aspects of lasers in the space environment as well as the potential military applications. The scope of this paper is limited to surveying a subset of "lasers in space" concepts to establish a basis on which they can be compared and development decisions can be made. Each concept could be examined in more depth, and some of the concepts have been discussed in other, more focused reports, but that is beyond the scope of this report. Also, the operational applications could be discussed in more detail, which would lead to concepts of operations (CONOPS) that consider operational employment, doctrinal implications, constraints, proper force size, interfaces with other systems, and so forth. Again, this type of discussion is beyond the scope of this study. While it is impossible to give sufficient detail about each concept to fully explain the range of benefits and costs, this discussion will give the reader a firm understanding of the relevant technological issues.

In the near term, most applications for lasers in the space environment involve non-weapons systems. Although this study discusses laser weapons in some detail, it focuses on non-weapons applications that could be developed in the near future to enhance the warfighters' capability. As the analysis will show, a plethora of maturing concepts exist that can increase military effectiveness.

The intended audience consists of the individuals in both the research laboratories and the operational commands, including the innovators in the battlelabs, who are building their program plans and looking to the future technological and operational requirements of the Air Force. Hopefully, these groups will find value in the study of the integration of laser technology in the space environment with the needs of the warfighter. However, the scientist at the bench will find the technical details lacking and the warfighter will find the operational details inadequate. This study serves simply as a compilation of various concepts for space-based laser systems and a brief analysis of the most likely near-term concepts.

Military Uses of Space

Access to outer space began in the 1950s with the Soviet launch of *Sputnik I* on 4 October 1957 and the US launch of *Explorer I* on 31 January 1958[3]. Immediately, a vast range of potential applications was possible that had been the dream of scientists and science-fiction writers for years. Many ideas were pursued that were of immediate use to the military. Those that have found the most success can be broadly grouped into systems that gather

information and those that relay it.

The first class of information-gathering systems includes weather satellites that image the earth in various spectral bands to determine cloud cover, moisture content, and related information. These systems include both geosynchronous satellites that remain relatively stationary over a region of the earth and low orbiting systems like the Defense Meteorological Satellite Program (DMSP) satellites that gather more highly resolved data for the military operator. Also, earth resources satellites like Landsat have imaged the earth in various spectral bands to determine such information as crop usage, environmental changes, and shifts in the rural/urban mix of the population. Both weather and resources satellites exploit the visible and infrared regions of the electromagnetic (EM) spectrum, passively collecting the data and then sending it to ground stations via radio and microwave links. Multispectral imaging (MSI) systems have been developed to collect data at different wavelengths simultaneously providing much more information. The MSI systems can determine such information as the health of forests and crops. They can also differentiate between wet and dry ground and the composition of structures, providing measurement and signature intelligence (MASINT) to the military users. Image Intelligence (IMINT) gathering from orbital platforms began early with the Corona program, a recently declassified imaging satellite system.[4] Most of these space assets are still cloaked in secrecy, but clearly the information is collected across a wide range of the EM spectrum, including radio and microwave transmissions as well as visible and infrared images. Some of the systems are passive, collecting the signals with extremely sensitive antennas and optical receivers, while others are active, using radar to penetrate cloud cover and observe targets on the ground. Other passive imaging systems have been placed in orbit to detect missile launches that might signal a hostile act against the US or its allies. For example, the Defense Support Program (DSP) surveillance satellites provided launch detection of *Scud* missiles during the Gulf War that permitted impact point prediction and early warning.[5] With the exception of space-based imaging radar satellites, all of these satellites are passive collectors of information. The laser, as discussed later, offers unique advantages in gathering information by actively illuminating targets.

The second class of information-relaying systems transfers voice, data and image information, and encompasses numerous commercial systems as well as dedicated military systems. For example, communications satellites typically use microwave frequencies to carry the information from the earth to the satellite, between satellites, and back to the earth. The Global Positioning System (GPS) provides a second example, relying on a constellation of satellites to generate and transmit highly accurate time signals for precisely determining location. These guidance or navigation systems offer incredible capabilities that are beginning to revolutionize military and civilian travel on or near the surface of the earth. In this second class of information-relaying systems, the laser offers unique capabilities for extremely high data rates and highly accurate guidance systems.

To date, no weapon systems have been stationed in space, primarily due to technological and treaty limitations. Both the Soviet Union and the United States have conducted tests of anti-satellite systems using various types of kinetic and chemical energy warheads to intercept and destroy orbiting platforms. The use of directed energy weapons (DEW) such as lasers, high power microwaves (HPM) or charged particle beams (CPB) has been considered in great detail by such programs as the US Strategic Defense Initiative (SDI). Some space-based DEW components, such as the ALPHA laser, have been constructed and

tested on the ground, but no systems have been tested in orbit. Without question, space-based lasers could be fielded in 10 to 20 years that can destroy targets in space as well as on or near the earth's surface. The challenges involve engineering and cost, rather than the fundamental laws of physics.

Treaties, such as the Outer Space Treaty of 1967 and the Anti-Ballistic Missile (ABM) Treaty, restrict the United States from placing certain types of weapons in space and need to be carefully considered as lasers move into the space environment. Other pending international agreements such as the "Blinding Laser" ban could affect space-based lasers even though space-based lasers would not be specifically designed for blinding personnel.[6] Technologists and operational commanders need to be aware of the political issues that can radically alter the new systems under development.

Military Uses of Lasers

For many years, the laser was touted as a "solution in search of a problem," as most of the early applications remained in the research laboratory.[7] In the past twenty years, lasers have solved myriad problems. The advances in laser technology have truly revolutionized a variety of areas, including medicine, telecommunications, industrial welding and cutting, and data processing. The ubiquitous laser bar code scanners and compact disc players provide almost daily contact with lasers for most people in the developed world. The military was one of the first services to see the potential for lasers in many applications. The early hopes of fielding a high-energy laser (HEL) weapon have yet to be fully realized by the United States, although the technology is well in hand. The AF's Airborne Laser (ABL) program aims to field an operational HEL to negate theater ballistic missiles in their boost phase by early in the 21st century.[8]

The laser was quickly employed as an aid to other weapon systems. Innovative scientists and engineers used the beam to point at a target and generate an aim-point that could be used to guide a bomb precisely to the target.[9] As a type of precision guided munitions (PGM), the PAVE ("Precision Avionics Vectoring Equipment") series of laser target designators (LTD) and the associated PAVEWAY laser-guided bombs (LGB) have been tremendously useful in conflicts from the Vietnam War to the Gulf War. Fielded military laser systems also include highly accurate range-finders and secure communication systems. Lasers have also been very useful for training aids such as the MILES system, the military equivalent of "laser tag" available now to the general public. Recently, laser spotlights have provided both visible and infrared illumination for improved use of night vision devices (NVD). As widespread as the laser has become in the US military, it has yet to be effectively employed in space. It is this shortcoming that motivates this study.

Military Use of Lasers in Space

This study begins with a brief discussion of the exploitable characteristics of both the space environment and the laser to create the backdrop for the subsequent analysis of various concepts for lasers in space. After defining a taxonomy for space-based laser systems and relating it to the operational concerns, the study examines several recent strategic studies with respect to how different groups of analysts envisioned using lasers in space for military purposes. These concepts are scored with a simple set of technological and operational

criteria in order to determine the most attractive near-term concepts for technology demonstrations.

II. EXPLOITABLE CHARACTERISTICS OF SPACE

The region outside the atmosphere offers a unique environment for military operations. The ability to exploit the characteristics of space will give the warfighter a competitive edge in virtually all conflicts. Highlighting the differences between "air" and "space" in terms of doctrinal development, one study identifies the three characteristics of space systems — emplacement, pervasiveness, and timeliness — that benefit from the features of space.[10] A brief review of these features provides background to understanding how space-based laser systems can be most effectively deployed.

A slightly different phrasing of these characteristics is given in an Air Force Space Command publication:

The space high ground offers tremendous advantages not found on Earth. Space allows countries like the United States to watch the entire globe on an *almost "real time" basis* [timeliness]—getting information nearly the instant it's needed. Space assets are *always available* [emplacement] when America needs them. Space also gives military planners the added advantage of seeing the entire battlefield—the *highest possible vantage point* [pervasiveness] allows friendly forces to watch over an enemy, serving as both a watchdog and a deterrent. Space systems also offer the distinct advantage of longevity. Aircraft missions last a few hours, while satellites are constantly operational for years.[11] [Emphasis added.]

While these unique characteristics of space are only beginning to be exploited effectively, an important caveat is that space is an international environment over which no nation has sovereign control. The fact that space systems do not need basing rights or over-flight approval increases the freedom to conduct operations, but this liberty not only creates vulnerabilities but increases the possibility of conflict with nations that attempt to interfere with the space systems of other nations.

Emplacement

Emplacement means that space systems can be pre-positioned in orbits which offer optimal support when needed. This characteristic might also be called persistence or presence. With proper ground support systems and sufficient satellites, space systems can be maintained in a state of wartime readiness, and thus are "inherently ready to support military operations at all times, which avoids the potential complications of basing rights and over-flight permission."[12] Given the remoteness of space as well as the difficulty and expense of deploying systems there, the characteristic of emplacement demands foresight by planners so that these systems can be pre-positioned to ensure availability in a crisis.

Pervasiveness

Outer space begins between 50 to 100 miles above the earth's surface, depending on the

criteria used.[13] This region surrounds the earth's surface and thus permits a presence over all land, sea, and air targets. Surveillance systems positioned in space reduce the risk of being surprised and complicate a potential adversary's ability to hide. Systems in low earth orbit (LEO) move at high velocities, traveling over 7 kilometers every second and completing an orbit every one to two hours, depending on altitude. LEO satellites give the best resolution due to their proximity to earth, but more satellites are required to permit continuous coverage of various ground and sea locations. Systems in middle earth orbit (MEO) have longer orbital periods, like the 12-hour period for the semi-synchronous orbits of the GPS satellites. This means that fewer satellites are required—only 24 satellites are needed for GPS to provide adequate coverage for global navigation. Satellites in geosynchronous earth orbit (GEO) have a 24-hour period and remain roughly over the same point on the earth's surface. With just three satellites, the entire surface of the earth can be covered, with the exception of the higher latitudes. However, due to the greatly increased altitude (22,300 nautical miles (NM)), achieving high resolution with GEO systems (e.g., the ability to discern or point at small targets) is challenging.

Timeliness

Depending on the type of orbit, a sufficient number of space systems can provide near-instantaneous coverage of every point on the globe, at the cost of increased complexity in controlling the network. Because the network is linked by EM radiation that travels at the speed of light (186,000 miles per second), a properly fielded space system permits "near-real-time transfer of information" to war-fighters and facilitates "rapid application of force" against almost any type of target.[14] Also, the high orbital speeds mean that space systems are frequently overhead, which translates into more engagement opportunities for the military commander.

Unattenuated Propagation of Electromagnetic Radiation

A vacuum is the ideal environment for propagating electromagnetic radiation. Any intervening medium, such as air, bends, scatters or absorbs the radiation, depending on the frequency or wavelength of the radiation and the type of medium. In the near vacuum of space, all frequencies propagate with essentially the same low attenuation.[15]

For space-based systems that transmit EM radiation toward the earth, how far this radiation penetrates into the atmosphere depends strongly on the wavelength due to both absorption and scattering. For example, clouds attenuate visible light much more than microwave frequencies used in radar systems. Thus, radar gives better all-weather coverage than lasers when propagating through the air. From space, radar systems are able to penetrate some clouds to image objects on the ground when optical imaging systems cannot discern the target through cloud cover. Many optical wavelengths do penetrate through clear air with low absorption, allowing space-based lasers to focus optical energy on targets at or near the earth's surface for applications such as illumination, communication, remote sensing, target designation, or target destruction.

By virtue of the negligible attenuation of EM radiation in space and the short wavelengths of lasers, laser beams can propagate for extremely long distances with relatively little growth in the cross-sectional area of the beam. This helps maintain the energy density in the

beam, meaning that more energy can be delivered to a target, both cooperative ones like communications satellites and uncooperative ones like reentry vehicles.

Challenges

The characteristics of space pose many challenges to both systems and people who transit through space. A brief discussion of a few of these challenges will support the subsequent discussion of laser systems that must operate in space for long periods.

Environmental Hazards. Ambient ionizing radiation poses unique risks to systems deployed in space. The atmosphere filters out a wide range of threats to people and systems near the surface. Ionizing radiation means any radiation that has sufficient energy to knock electrons out of their orbits around the atomic nucleus. It includes very short wavelength EM radiation, such as extreme ultraviolet and x-rays and energetic particles consisting primarily of protons, alpha particles, and electrons. Much of the ionizing radiation comes from the sun. Very high-speed particles, cosmic rays, come from other sources. This naturally occurring radiation can destroy electronics, cause software errors by changing memory values, and degrade hardware. While the EM radiation from the sun is fairly constant, the intensity of particles varies greatly with time and peaks with solar flares. The particles interfere with satellite operations and can disable satellites. Forecasting the space environment is an emerging area of meteorology. Thus, space systems that must remain in orbit for many years can face a large cumulative exposure as well as brief, high doses. Shielding can reduce the effects of ionizing radiation but at the expense of increased weight. Careful selection of materials can also reduce the deleterious effects. For this reason, extensive radiation hardening programs for critical components are underway within NASA and DOD.

A further complication is the existence of the Van Allen radiation belts, which are regions of high-energy particles trapped in the earth's magnetic field. Primarily consisting of protons and electrons, these particles spiral around the magnetic fields, reflecting back and forth between the earth's magnetic poles, where the magnetic flux becomes more concentrated. The interaction of this radiation with the air gives rise to the beautiful *aurora borealis and aurora australis*. There are two Van Allen belts. The inner belt begins at an altitude between 250 and 750 miles (depending on latitude), extends to about 6,200 miles and covers from about 45 degrees north to 45 degrees south in latitude; the outer belt begins at about 6,200 miles and extends out to as much as 52,000 miles.[16] Due to orbital constraints most space systems will operate within one of these two belts. Spacecraft in LEO appear to receive an insignificant amount of radiation from the Van Allen zones, while spacecraft in MEO or GEO may pick up substantial doses.[17]

Another challenge posed by space is extreme temperatures. With no atmosphere to help conduct heat, systems can become either extremely hot or extremely cold, depending on exposure to the sun. As a spacecraft orbits, it moves into the earth's shadow where the sun's heating is eliminated and radiative cooling occurs. When it again enters the sunlight, the heat builds up on the surfaces exposed to the sun. Such thermal cycling causes expansion and contraction of materials and needs to be considered in the design of spacecraft. The cycling may eventually cause cumulative damage to the spacecraft and could cause the misalignment of sensitive optical systems.

Cost. Currently, people launch objects into space by using chemical rockets to give the object sufficient altitude and velocity to attain orbit. The costs of building and launching the space boosters include both the cost of the booster and the cost of the facilities and manpower to accomplish the task. Current costs of orbiting a LEO satellite are very high, ranging from $3,000 to $10,000 per pound.[18] The Space Shuttle payloads cost roughly $8,000 to $9,000 per pound to launch.[19] Several programs are underway within NASA and DOD to explore ways of bringing the cost down below $1,000 per pound. These programs include reusable chemical rocket systems, such as the single-stage-to-orbit (SSTO) concept tested in the Delta Clipper rocket; a reusable space plane that would take off and land like a conventional aircraft; and novel ideas, such as electromagnetic rail guns and air guns to put satellites in orbit without chemical rockets. The relevant point for this discussion is that because cost determines the feasibility of putting systems in space, anything that can be done to reduce weight is highly valued. As will be discussed later, laser systems may offer significant reductions in weight while maintaining or expanding system capabilities (such as communication bandwidth).

Manpower-Intensive Operations. At present, each US space launch requires large teams of highly trained personnel to design, build, launch, and operate space systems. The launch facilities are expensive, as are the global network of ground stations that are currently necessary to maintain operational control over the spacecraft. Research is underway to make spacecraft more modular and standardized, which would reduce design and manufacturing costs. Advances in software and increasing space infrastructure (such as GPS as a navigational grid) will make spacecraft more autonomous and reduce the need for large numbers of highly skilled engineers to operate the systems. Manpower reductions should be included in the design of all space systems.

Self-Protection. Systems placed in space face both accidental and intentional threats. As more satellites have been launched, the amount of man-made debris ("space junk") has increased. The Air Force currently tracks 8,168 objects in orbit, only 7 percent of which are active satellites.[20] When combined with naturally occurring meteorites, the risk of colliding with a hypervelocity projectile is not insignificant, particularly if spacecraft remain in orbit for years. Proper orbit selection, additional shielding, or maneuvering are options to increase the spacecraft's survivability.

Since from 1950s, military researchers have considered ways to destroy satellites.[21] Anti-satellite (ASAT) weapons using nuclear warheads, conventional explosives and hypervelocity kinetic kill warheads as various ways to destroy a satellite were tested by the United States and the Soviet Union. There were suspicions that Soviets blinded optical sensors on US early warning satellites in the mid-1970s but, even if true, the laser systems would likely have been R&D prototypes rather than fielded hardware.[22] Of course, a successful R&D system leaves a residual operational legacy, as the Russians may possess at their laser research facility in Sary Shagan, which is located in Kazakstan.[23] The US Air Force has an on-going ground-based laser anti-satellite (GBL ASAT) research program. Certainly directed energy systems such as lasers or high power microwave (HPM) weapons could be used to disable or negate satellites, but they have not been fielded at this time due to substantial technical challenges and treaty agreements. At present, only a residual capability exists within the United States or Russia for ASAT missions. However, the predictability of orbits and the remoteness of space complicate the ability to protect

spacecraft from attack.

III. EXPLOITABLE CHARACTERISTICS OF LASERS

The laser is a unique source of optical radiation which has a number of characteristics that can be exploited for military space systems. As a number of these applications carry over to the civilian market, NASA and the private sector are interested in exploiting the laser for space applications. There are a number of sources that describe the basics of lasers.[24]

Briefly, the laser uses the phenomenon of *stimulated emission* to generate a very narrow beam of light that is usually highly monochromatic. Such a beam has a high degree of *coherence* as compared to other optical sources like the sun or incandescent light bulbs. The coherence permits the beam to propagate long distances with little spreading and to be focused onto a small area. Within the ever-expanding variety of types of lasers, with different wavelengths, power levels, temporal characteristics and operating efficiencies, the unifying characteristic is the generation of coherent radiation.

In analyzing any laser application, it is convenient to break the process into three parts: the laser system, the propagation medium through which the beam travels, and the target where the beam is absorbed. The laser system can be further divided into the laser, where the coherent radiation is generated, and the optical system that takes the beam from the laser to the output aperture where the beam enters the propagation medium. At the target, the light from the laser must be absorbed to cause an effect, whether that effect is an electrical response in a detector or a destructive effect for a weapons application. Each part (the laser system, the propagation medium, and the target) plays an important role in evaluating the feasibility of a laser application. Keeping this taxonomy in mind will help avoid fixating on any single part to the exclusion of the others.

Directionality

One of the key properties of lasers is that the output beam is highly directional. Typical laser beams have a divergence of less than a milliradian,* and some systems can be designed to have sub-microradian divergences. Because of their small size, semiconductor diode lasers usually have divergences measured in degrees, expanding rapidly. However, this beam divergence can be substantially reduced by using external optics. A laser system with an output beam diameter of one meter could readily have a 0.05 milliradian beam divergence, expanding to only about 25 meters after traveling 500 kilometers. This pencil-like beam of light permits highly accurate placement of energy on a target for a variety of applications such as target designation and efficient communication links. Additionally, the beam can be used for covert applications because it is very difficult to detect the beam without intercepting it. The disadvantage, of course, is that pointing the beam requires a high degree of precision.

Wavelength, Bandwidth, and Tunability

A laser operates in the infrared, visible and ultraviolet regions of the electromagnetic

spectrum, from one millimeter to 100 nanometers in wavelength. Typically, lasers are described by their wavelength (λ) as contrasted with radar systems that are characterized by frequency, because the laser's frequency is from 10,000 to 1,000,000 times higher than typical microwave radars. Both microns (mm or 10^{-6} meters) and nanometers (nm or 10^{-9} meters) will be used in this study to characterize lasers. Radar systems usually have wavelengths on the order of millimeters to centimeters. Many lasers generate light in a very narrow band around a single, central wavelength. Because this characteristic manifests itself in visible lasers as a very pure, single color, the narrow linewidth is termed *monochromaticity*. For example, the neodymium laser used in most laser designators (the ubiquitous "Nd:YAG") generates an output beam at 1.064 microns, with a typical bandwidth of 0.00045 microns, an amazingly narrow linewidth of 0.04 percent of the central wavelength. This spectrally pure output is critical for a multitude of applications, including remote sensing for specific chemical constituents and high signal-to-noise ratio (SNR) communications. Some types of lasers operate on several different wavelengths simultaneously, such as the argon ion laser that emits most of its light at 488 nm and 514.5 nm. Multiline emission can be both a benefit and a detriment, depending on the application.

While most lasers will only operate on discrete wavelengths, some types can be tuned over a range of wavelengths, giving an additional agility that has multiple uses. Examples of tunable lasers include the titanium sapphire (Ti:S) laser, the chromium:LiSAF laser (where the host material is a crystal of $LiSrAlF_6$), and the chromium:LiCAF lasers (where the host material is a crystal of $LiCaAlF_6$). These three lasers are solid state systems that have great potential for space applications, such as remote sensing of the atmosphere from orbit. They also have the added potential of being pumped by diode lasers or other solid state lasers that are diode-pumped. Thus, all-solid-state systems can be constructed with much improved reliability and durability. Table 1 shows the tuning range of these three lasers.

Table 1. Typical Tunable Lasers[25]

Laser Type	Lasing Ion	Wavelength Range
Titanium Sapphire	Ti^{3+}	660 to 1180 nm
Chromium LiSAF	Cr^{3+}	780 to 920 nm
Chromium LiCAF	Cr^{3+}	720 to 840 nm

As discussed in more detail in Appendix B, some special types of materials respond nonlinearly to light passing through them and can generate new wavelengths of light. Such nonlinear optical (NLO) materials are the subject of contemporary research. The most common is the frequency doubling crystals that cut the wavelength in half, so that the infrared emission of a Nd:YAG laser (at 1064 nm) can be converted into a visible beam (at 532 nm). Frequency doubling can be fairly efficient, with reported values of 50 to 80 percent conversion from the fundamental wavelength to the doubled wavelength. Other nonlinear systems, like optical parametric oscillators (OPO), can generate a tunable output. While the technical details of such systems are beyond the scope of this study, they highlight the possibility of "wavelength agility" or the ability to tune the output wavelength of the laser. However, at this time, only a limited number of NLO materials are available. The efficiency at which they operate tends to be low. Also, obtaining efficient nonlinear effects requires high peak powers from the laser beam, which can damage the NLO

material. The threshold at which NLO materials are damaged is usually low, making scaling to systems with high average power challenging. Research in material science is likely to push back these limits.

Another NLO effect that can be used for wavelength shifting is stimulated Raman scattering (SRS). Raman scattering occurs when a beam of light passes through a material and excites a very weak transition within the material, leaving some of its energy. The emitted light is shifted to a longer wavelength. If the process is stimulated in a method analogous to the operation of a laser, a significant amount of the light can be shifted to the new wavelength. SRS is a complicated process beyond the scope of this study but offers great potential for laser systems.

The narrow bandwidth of the typical laser can be reduced even further by specialized design of the laser. If this narrow beam is reflected off a moving object, the frequency of the reflection will be shifted slightly by the Doppler effect, permitting direct measurement of the velocity of the object. The "object" can even be a region of air, allowing direct, remote measurement of wind speed.

Temporal Modulation

The output from the laser can be either continuous (called "continuous wave" or CW) or pulsed. Usually a laser is called CW if the output lasts more than 0.25 second.[26] A pulsed laser is characterized by the pulse duration, which is measured in seconds. If the laser is repetitively pulsed, the pulse repetition frequency (known as the *prf* and measured in Hertz) is the period from the beginning of one pulse to the beginning of the next pulse. The duty cycle of the laser is the product of the pulse duration and the prf and gives a measure of what percent of the time a laser is emitting. A duty cycle of 50 percent means the laser is emitting energy half of the time.

Most lasers of interest to the military are either CW or have very short pulses on the order of nanoseconds. For example, the laser being developed for theater missile defense in the Airborne Laser is a CW laser. In contrast, the typical laser designator emits pulses of about 10 nanoseconds in duration, with a prf of 10 Hz, giving a duty cycle of 0.0000001. Some lasers use much higher repetition rates, on the order of kilohertz or higher, such as semiconductor or diode lasers that have great potential for communication systems. Imaging laser radars under development may use pulses with durations of less than a nanosecond in order to achieve good spatial resolution. (Light moves about 1 foot in a nanosecond, so temporally resolving the reflections of pulses off a surface can give detailed three-dimensional information if the pulses are short enough.)

Output Power and Energy

The laser beam contains energy in the form of electromagnetic radiation that travels at the speed of light and has no mass. CW output is usually characterized by the power in the beam measured in Watts, while pulsed output is characterized by the energy in each pulse, in Joules. Repetitively pulsed systems are also characterized by their average power. The range of output power from useful CW lasers ranges from milliwatts to hundreds of kilowatts. Megawatt lasers are feasible but pose unique challenges when scaling the output power to that level. The MIRACL laser system is a megawatt-class laser at the High Energy

Laser System Test Facility on White Sands Missile Range that is routinely used for damage testing and other studies. Commercial users can even buy time on this device for their own testing.[27]

All of the laser power is concentrated in a small solid angle due to the narrow beam. This means that even small lasers, like the helium neon (He-Ne) lasers frequently used as pointers, have output beams that are brighter than the sun. Here the term *brightness* is rigorously used to mean the amount of power being emitted per unit area of the source per solid angle.

A laser is classified as a severe hazard (denoted Class IV by federal regulations) if the output power exceeds 0.5 watts—quite a contrast with a 100-watt lightbulb that emits its energy in all directions. The reason is the high brightness of these lasers. Class IV lasers, the most dangerous category, are sufficiently intense that the direct beam is a hazard to both eyes and skin, causing nearly instantaneous injury. The beam could also ignite some objects that it strikes. (Several fatalities have been reported due to laser-generated fires.) The Class IV laser is so dangerous that even the diffuse reflection of the beam from a wall might cause eye injury. Stringent control measures are required for the use of these lasers, even though the output power may appear to be low.

To give a feeling for these numbers, the damage threshold for "soft" targets like paper or skin is *roughly* one Joule per square centimeter, assuming a one-second exposure. Wood surfaces are damaged at approximately 10 J/cm^2 while metal surfaces are damaged in the range of 100 J/cm_2.[28] Note that these numbers are just order of magnitude values to illustrate the concentrated power of the laser because actual damage thresholds depend on a number of factors. For example, the New World Vistas study by the AF Scientific Advisory Board cited a damage threshold for Scud missiles as roughly 1,000 J/cm_2 as a first-order design parameter.[29]

Pulsed lasers emit light in short bursts. The energy per pulse for useful lasers begins in the millijoule range and reaches into kilojoules. A typical laser designator, like the LANTIRN system used by the AF, emits very short pulses (of about 10 nanoseconds in duration) that contain over 100 millijoules of energy. Assuming a square pulse, these pulses have a peak power of 10 megawatts (dividing 100 millijoules by 10 nanoseconds). It is the high peak powers in pulsed lasers that can be exploited for a variety of applications. If the output of even the modest LANTIRN is focused in the air, it can be sufficiently intense to ionize the air in a phenomenon known as air breakdown.

"Deep Magazine"

The amount of power or energy depends strongly on the application. For communication systems, the use of sensitive detectors can permit the use of low energy pulses and lasers with average powers of a few watts. The operational lifetime of such systems could easily be decades. For weapons applications, megawatts or tens of kilojoules can be required to achieve structural damage on distant targets. By carrying an adequate fuel supply or by using energy from the sun either directly or indirectly to power the laser, many firings of the high-energy laser can be possible, thus giving a "deep magazine" when compared to conventional systems. Estimating the energy requirements is one of the key assessments of

the laser concepts to be discussed later in order to appraise the feasibility of the concept.

Adjustable "Power on Target"

The ability to adjust the energy output of a laser system is also an exploitable characteristic.[30] A single, properly designed system could be used in a passive mode (no output beam) for surveillance, in a low power mode for target illumination for active imaging and for target designation for PGM delivery, and in a high power mode for negating a target.[31]

No Recoil from Light Beams

One unique aspect of directed energy beams like lasers is that there is no recoil in the weapon due to the output beam, as there is with kinetic energy weapons. This means that there is negligible effect on the orbital parameters in even a HEL due to the beam. However, there can be substantial thrust generated by the exhaust gases from a high-energy, chemical laser as it creates the output beam. The SBL systems, such as the Alpha laser, are designed to reduce the impact on the orbit of the space-based laser.

Speed of Light Delivery

Laser beams travel at about 300,000 km per second, or about Mach 1,000,000.[32] This permits near-instantaneous engagement of targets, even for targets at very long distances. This greatly reduces the need to lead the target as compared to kinetic energy weapons like missiles. (There may still a need for a significant point-ahead angle if the relative velocities between the laser system and the target is large, as in the case of pointing a laser at a satellite from a ground-based laser.) If the target can be tracked visually, the laser beam can be placed on the target and, if sufficient energy is delivered, the desired effect can be achieved. This exploitable characteristic is particularly useful for operations in which time is critical or the engagement range is extremely long.

Freedom from Newtonian Constraints

Conventional weapons rely on kinetic energy in the form of a high-speed impact or chemical energy in the form of explosives to attack targets. These weapons are subject to the Newtonian laws of physics, such as gravitational attraction and aerodynamic forces. Gravitational attraction and aerodynamic forces, such as crosswinds, complicate the targeting by requiring trajectory considerations during the weapon delivery. Aerodynamic forces such as drag and lift affect how much range can be achieved from the weapon. The laser beam is not significantly affected by gravity unless the propagation path is extremely long where bending of light in gravitational fields is significant. Aerodynamic forces do not slow the beam, although the atmosphere can scatter and absorb the optical radiation as discussed below. Thus, the laser is free from the usual constraints of Newtonian physics.

"Ilities"

One topic of constant concern for system developers is the "ilities" such as reliability,

maintainability and affordability. This is particularly important for space systems because access for repairs is almost non-existent. The lengthy series of tests to "space qualify" hardware is one of the factors that drive up the cost of space systems. Some types of lasers are very reliable, relatively free of maintenance requirements, and have a long service life. For example, semiconductor diode lasers are now able to operate for tens of thousands of hours. The fact that every compact disk player contains three diode lasers is quiet testimony to the reliability and affordability of these types of lasers. Semiconductor lasers are a leading candidate for some of the space-based applications such as communication. Also, all-solid-state laser systems are now being marketed commercially, such as diode-pumped Nd:YAG lasers, that are very rugged and reliable, require little maintenance, and have a long service life while generating substantial output power. Replacing the flashlamps with laser diodes was a key change to this advancement. Such lasers would be appropriate for applications such as space-based target designation and remote sensing. Other systems, such as some closed-cycle gas lasers that can be scaled to fairly high powers, can be operated continuously in the laboratory for thousands of hours. These lasers have potential for laser illuminators, active imagers, and possibly even weapons. A final point related to affordability derives from the much shorter wavelength of lasers as compared to microwave systems. This means that the size and weight of the spacecraft can probably be reduced as compared to microwave systems that perform analogous functions, such as imaging or communication.

Challenges

The laser has a number of unique characteristics that can exploited for military applications, but there are challenges and inherent limitations. These limitations can be overcome or ameliorated by proper design. The challenge to understanding laser devices is to consider that the entire system, which consists of the laser device and its supporting systems on a space-based platform, its beam through space or air to impact on a target of some sort, and its ability to influence that target in some way. It is essential to consider the entire laser system, rather than just the laser itself, in order to identify the limiting technical challenges. In some concepts, it may be generating sufficient power from the laser device, as in the case of space-based laser weapons for national missile defense. In other cases, the prevailing challenge may be the acquisition, pointing, and tracking (APT) system or propagating the beam through the atmosphere, as in laser communication systems. In still others, the challenge may be in gathering weakly scattered light from the target in order to gather the desired information, as in the case of direct wind measurement or remote sensing of effluents. Finally, the nature of the target may be the limiting constraint, as each target has its characteristic reflection and absorption properties. In assessing any concept, the entire end-to-end system needs to be considered.

Efficiency. The process of generating the highly coherent laser beam is usually very inefficient.* The Nd:YAG laser is only about one percent efficient, while the popular helium-neon laser is only about 0.001 percent efficient. The unique features of the output beam make these inefficiencies bearable. Fortuitously, semiconductor lasers, which generate light by direct conversion of electrical current to photons, are very efficient, achieving 20 to 50 percent efficiencies. At present, these systems do not produce the power levels necessary for high-energy laser weapons. But a laser, such as the carbon dioxide laser (used in the Airborne Laser Laboratory (ALL) to shoot down several Sidewinder missiles), has an efficiency on the order of 20 to 30 percent, which can achieve output powers of

hundreds of kilowatts. The chemical efficiency of hydrogen fluoride (HF) lasers, being considered for space-based laser weapons, can be up to 20 percent or more, while the electrical efficiencies can exceed 150 percent, because the energy in the beam comes from a highly exothermic chemical reaction.[33]

It is critical to determine where the remaining energy goes, which inevitably ends up as waste heat and must be removed from the laser system. In some lasers, like the HF laser, the exhaust gases carry away the heat. In other lasers, such as the Nd:YAG or semiconductor laser, some method must be used to extract the heat from the laser, such as flowing cooled water within the laser. If it is allowed to remain in the laser, the performance of the laser is likely to be degraded or, in the extreme, the laser may be damaged. Dissipating heat in a spacecraft can pose serious problems.

Refueling. Some types of lasers consume fuel while they are operating. For example, hydrogen fluoride lasers need hydrogen, fluorine, and carrier gases such as helium. The designs usually include enough consumables for the expected number of engagements. However, as scenarios shift and requirements change, the capability to refuel these types of laser systems through a space transportation system would be very useful, although quite expensive.

The difficulty in refueling certain types of lasers makes them less attractive. It also increases the desirability of other lasers that obtain their energy from electricity or directly from the sun. Semiconductor lasers, Nd:YAG lasers, and tunable lasers, such as the titanium sapphire laser, can be efficiently operated using electricity. An atomic bromine laser, operating at 2.714 microns, has the potential of being directly pumped by sunlight without expending any fuel. This laser is currently under investigation at the AF Phillips Laboratory.

Target Acquisition. The disadvantage of the small divergence of the laser beam is the challenge of accurately pointing it at the desired target, whether that target is a communications satellite or a nuclear warhead. The basic issue is acquiring the target in order to know where to point the beam. (This is part of the acquisition, pointing, and tracking (APT) process that is inherent in many potential laser applications.) For cooperative targets, such as a satellite in a communications network, a corner cube reflector could be used that reflects any incident light directly back at the source. By using a laser beam that has a larger divergence, essentially a laser floodlight, a wider region of space can be scanned until the retroreflection is sensed and the narrow beam pointed at the target. For uncooperative targets, other methods of acquiring the target need to be considered, such as passive optical sensors and active microwave radar systems. Using the GPS system and recently-developed inertial reference units, space-based laser systems will be able to point at targets on or near the surface of the earth with very high accuracy. Non-mechanical beam steering, which involves tracking with no moving parts, is also being developed to permit high speed tracking of targets such as missiles or satellites.

Propagation into the Atmosphere. Some of the possible applications of space-based lasers involve aiming the laser back into the atmosphere. This includes such concepts as remote sensing of chemical effluents, measuring wind speeds, and negating enemy targets on the ground, on the sea, or in the air. However, the atmosphere attenuates many wavelengths, which greatly reduces the amount of energy that can be put on the target. For example, the

leading candidate for a space-based laser weapon is the TRW's hydrogen fluoride Alpha laser, which lases at 2.7 microns, a wavelength that is strongly absorbed by water vapor in the air. Thus, this laser could only attack targets at or above 30,000 feet.[34] Visible wavelengths penetrate far deeper into the air, but another phenomenon that attenuates light is Rayleigh scattering that increases as the fourth power of frequency. This means that shorter wavelength beams will scatter more significantly than infrared beams, reducing the energy that reaches the target and increasing the size of the laser beam. The optimum wavelengths appear, at first order analysis, to be the near infrared regions of 0.7 to 1.4 microns. Fortunately, a large number of lasers exist in this region, although few that are scalable to high powers. For example, the laser for the Airborne Laser is a chemical oxygen-iodine laser (COIL) that operates at 1.315 microns in this preferred region.

Target Coupling. Another challenge to using lasers in space is to determine the most efficient way to couple the laser energy onto the target. In order to cause an effect, the laser energy must be absorbed by the target. For cooperative targets, this means finding a suitable detector that has a good response to the particular wavelength. Detector materials are fairly mature and improving, so this is unlikely to limit laser applications. However, for uncooperative targets like warheads, the laser radiation is usually absorbed at or near the surface of the target. Some of the light will be reflected as well. Thus, the laser beam will have to work its way into the target in order to cause structural damage. For fairly "soft" targets like satellites, this may not be difficult—parts like solar panels and optical systems can be readily damaged. But burning through a reentry vehicle's outer skin would be very difficult.

Laser Safety. Laser beams can injure people, particularly if a person looks directly into the beam of a visible or near infrared laser with wavelengths from 400 to 1400 nm.[35] Even a millijoule entering the cornea can cause a catastrophic hemorrhage of the retina, because the optics of the eye increase the intensity of the laser beam by reducing the size of the beam by about a factor of 100,000 as the light travels from the cornea to the retina. Retinal injuries are permanent, leading to some loss of sight. Even Class IIIa lasers with output powers in the 1 to 5 milliwatt range can burn the retina. Thus, space-based lasers in this wavelength range could pose a safety hazard if pointed toward the earth.

Unfortunately, the term "eye-safe" has recently become popular when referring to lasers that emit wavelengths longer than 1400 nm, even if the output power or pulse energy puts the laser in Class IV as a severe hazard. The notion is that the retina would be safe and that the cornea might be injured but would heal. This ignores the reality that deep cornea burns are permanent, although corneal transplants are possible. Some people are even referring to deuterium fluoride HEL weapon prototypes (operating at 3.8 microns) and 50 watt carbon dioxide laser radars (operating at 10.6 microns) as "eye-safe" given the operating wavelength, even though this ignores the high power output. Such systems are certainly not eye-safe in any aspect, and the term sends the wrong message to those not well versed in laser safety.

Almost all the risks with lasers can be avoided by carefully controlling where the laser is pointing before it is activated. A thorough laser safety analysis should be included early in any laser program, particularly if the laser has new or unusual output characteristics, such as extremely short pulses with high peak powers. The biological database that is used to set safety standards may not be appropriate for some new types of lasers, and gathering new

data to set new safety thresholds is time-consuming, challenging research. Thus, the program manager must assess the safety risk early in coordination with DOD laser safety experts.

IV. A TAXONOMY FOR LASERS IN SPACE

This section develops a taxonomy for space-based laser systems that is connected with the warfighter's terminology. A number of recently conducted strategic studies, which highlighted various laser applications, are summarized so that the relevant space-based laser concepts can be organized with the taxonomy.

Subsequent sections will explore the concepts in more depth, and provide relative scores for each concept based on its technical merit and operational value. The technical assessment considers both feasibility and maturity. The operational appraisal considers the operational enhancement and the cost, which includes funding, operations and maintenance support, and personnel. The most feasible near-term concepts will be developed further in order to accelerate the process of putting the technology into the hands of the operational commands. This process uses a variety of paths, such as Advanced Technology Demonstrations, Advanced Concept Technology Demonstrations, the new Battlelabs which are chartered to provide operational MAJCOMs with innovative ideas, and other informal avenues.

A Taxonomy of Concepts

A functional taxonomy is more useful for technologists who map various laser concepts onto operational applications than other possible taxonomies that are based on laser parameters. Letting 'form fit function' gives technologists the greatest flexibility in finding a variety of lasers to implement the concepts, and it also keeps the operators from getting bogged down in technical details. Space-based laser concepts will be grouped into four classes: enabling systems, information-gathering systems, information-relaying systems, and energy-delivery systems. The discussion below elaborates on each class, and numerous examples of concepts within each class will be discussed in subsequent sections.

Enabling Systems. The effectiveness of some current weapon systems can be enhanced substantially by specific applications of lasers, thus suggesting the term "enabling systems" for this class of concepts. A further breakdown of this area could include three sub-classes of systems, including those that: provide an optical signal for guidance of other systems, provide illumination for other optical sensing systems, and provide information that would normally be provided by non-laser systems. Laser target designators are an example of the first sub-class that uses laser radiation to enhance the accuracy of conventional munitions. An example of the second sub-class would be the illumination of a target area with laser radiation from a carbon dioxide (CO_2) laser for improved imaging with forward looking infrared (FLIR) systems. Laser altimeters and laser velocimeters fall into the third sub-class. However, lasers that are used solely as internal components in a system and do not emit the laser beam outside of the unit, such as ring laser gyroscopes for inertial reference units, will not be included in this study, although they offer substantial improvement in capability. The enhancement of the laser systems that fall into the "enabling" class reflects the incremental improvement that is provided to weapon systems.

Information-Gathering Systems. Optical sensing systems gather information through the collection of optical energy. This energy may be emitted by the source, as in the case of an aircraft engine's infrared emission, or may be scattered off or reflected from the source, as occurs when a photograph is taken of a target site for battle damage assessment (BDA) after it is attacked. Currently, such optical systems are passive systems that do not emit any radiation in order to make their measurements. Examples include reconnaissance satellites, infrared missile tracking sensors, and weather satellites. In many cases, active illumination with a laser source can improve the information gathered or provide new information that could not be obtained without the laser radiation. The class of "information gathering systems" can be further broken into two sub-classes: those that use active illumination to image the target with optical systems on the same platform, and those that use the laser as a probe to gather 'non-image' information. The first sub-class is exemplified by the AF's Starfire Optical Range at Kirtland AFB in New Mexico in which a laser beam illuminates space objects and uses the scattered radiation collected at the same site to form an image.[36] An example of this second sub-class is remote sensing using differential absorption laser radar (DIAL) technology to measure effluents from targets that were just bombed or that is engaged in manufacturing questionable substances.

Information-Relaying Systems. Communication and data-relay systems abound in the space environment, including both military and commercial satellites that relay data, voice, television, and other information across the globe. All of the current systems use microwave frequency transmissions that propagate fairly well through the atmosphere, although both clouds and the ionosphere can interfere with these frequencies. Two attributes of microwave frequencies are important when compared with optical frequencies. First, the amount of information that can potentially be carried on a given frequency (called the carrier) depends on that frequency, so that the higher the carrier frequency, the more information that can be potentially transmitted. Of course, suitable modulation schemes need developing to take advantage of this information bandwidth. Thus, laser communication systems have inherently far greater information capacity than microwave systems. The second attribute is the spreading of the beam. As discussed more fully in Appendix A, the physical phenomenon of diffraction causes all EM radiation to spread out whose spreading is inversely proportional to the frequency.[37] Thus, for a given beam diameter or antenna size, a microwave beam will spread out much faster than a laser beam, due to the factor of 10^4 to 10^5 increase in frequency. Thus, laser communication systems can more efficiently put the signal on the receiver and require less output energy.

In order to transmit information, the space-based laser concepts in the information-relaying class must include some method of temporally varying (or modulating) some output characteristic of the beam. Pulsing the output power exploits the well-developed digital communication technology which uses semiconductor lasers to send information through fiber optic networks. However, other modulation schemes that vary the polarization, phase, and wavelength all offer unique advantages.

Energy-Delivery Systems. There are some cases in which the only requirement is delivering energy to the target using either a CW or pulsed laser beam. High-energy laser weapons destroy or degrade the target by causing structural damage or blinding sensors. Power beaming recharges a satellite's batteries or delivers energy to a remote location on the earth. Using high-energy pulses, a laser system could also generate thrust on a distant spacecraft by blowing off an ablative material on the base of a spacecraft, which provides an

alternative to chemical rockets for spacecraft propulsion.

Figure 1 summarizes this taxonomy and further refines these four functional categories into possible sub-classes. Some representative concepts are provided for the purposes of illustrating the taxonomy.

Figure 1. A Functional Taxonomy for Lasers in Space

Mapping Space-Based Lasers onto Operational Taxonomy

One of the most important goals of this study is to show how space-based laser systems can enhance the ability to accomplish various military missions. As we consider specific concepts, it is useful to discuss how these systems relate to the taxonomy used by the Air Force.

The Air Force recently identified six core competencies as it moves beyond the *Global Reach-Global Power* concept to the new strategic vision of *Global Engagement*. A "core competency" is the "combination of professional knowledge, specific air power expertise, and technological capabilities that produce superior military outcomes."[38] The core competencies provide one means for expressing the Air Force's "unique form of military power" and "understanding how the various aspects fit together."[39] The six core competencies are:

- air and space superiority
- global attack
- rapid global mobility
- precision engagement
- information superiority
- agile combat support

The first core competency integrates air and space in order to control the entire expanse from ground to outer space, and thus give "freedom *from* attack and freedom *to* attack."[40] The ability to designate targets from space platforms, provide high capacity information channels to operators in theater, and, in the long term, directly negate targets on or near the surface of the earth means that space-based lasers have the potential to support this core competency. Other concepts, such as space-based lasers for BDA, that also support achieving air and space superiority will be discussed later.

The concept of global attack involves the ability to rapidly deploy expeditionary forces to a theater of operations where the United States may not have existing bases. Space-based laser systems can improve the knowledge of the theater by directly measuring winds and improve low-light navigation by battlefield illumination with infrared laser radiation, to highlight just two possible roles. Not only does the pervasiveness of space systems translate into global coverage, but the high speed of orbiting systems could be exploited to put laser systems over the area of operations very rapidly, both for weapons and support applications.

Rapid global mobility is essential for all military operations as the United States retains a growing portion of its forces within the US. Missions such as peacekeeping and humanitarian support will likely increase, given that combat operations could always occur.

Space-based laser communication systems can provide secure, high capacity connection with command and control facilities in CONUS, while battlefield illumination from space can aid the initial insertion of forces into an undeveloped region, as discussed later in this study.

The ability to achieve precision engagement as a proven core competency has relied largely on laser systems to designate targets from the air or ground. Advances in space systems coupled with improvements in laser technology will give the capability of designating targets, including mobile ones, from space. It is conceivable that laser-guided weapons could be launched from beyond visual range of the target and guided to targets using space-based laser designators in real time. This improved stand-off capability reduces the risk to US forces and increases the vulnerability of the adversary. As a support system, the high capacity laser communication system could relay massive amounts of information to the next generation combat aircraft (which may be uninhabited) to give the pilot or the aircraft the very latest information on the target, the weather, and military threats.

Military operations demand secure, relevant, and timely information. For this reason, information superiority on the battlefield is one of the first objectives. Laser communication systems have the potential of being more jam-resistant given the narrow beam and the optical frequencies. The narrow beam also makes these systems less likely to be intercepted by the adversary. A number of other concepts using space-based laser systems could improve offensive and defensive information warfare activities.

See Graphic.

Finally, the core competency of agile combat support makes forces more responsive while leaving a smaller "support footprint" in theater. The support includes logistics, airbase security, civil engineering, and other administrative and medical functions. This core competency probably has the least direct connection to space-based laser systems than the others, but there is a role nonetheless. In addition to the potential for high-capacity communication systems that use space-based lasers, one possible concept is to use space-based laser illumination aimed at corner cube reflectors mounted on terrestrial vehicles as an "identification-friend-or-foe" (IFF) system to reduce the risk of fratricide and improve the detection of infiltrators into the airbase area. By vibrating the corner cubes in a coded pattern that can be varied daily, this IFF system could be made more secure.

To summarize, the four functional classes of laser systems connect to the six core competencies, as shown in Figure 2. The information-relaying systems apply to all the core competencies given the increasingly central role of information in military operations. Enabling systems may have the next widest applicability, while space-based target designation will affect the first, second, and fourth core competencies, and battlefield illumination will aid the third and sixth core competencies, as discussed above. Information-gathering and energy-delivery systems appear, at first cut, to be somewhat more narrowly applicable, but these systems are likely to provide unique capabilities such as improved weather monitoring, remote BDA, and negation of counterforce targets. Clearly, lasers in space are relevant to achieving the AF mission.

Figure 2. Mapping Laser Taxonomy to AF Core Competencies

In the current doctrine of the Air Force, the four roles are aerospace control, force application, force enhancement, and force support.[41] Aerospace control encompasses those operations that are intended to "control the combat environment", while force application roles "apply combat power", force enhancement roles "multiply combat effectiveness" and force support activities "sustain forces".[42] In each role, there are various missions, many of which relate to space operations. There is no unique approach to map the missions to the roles. For example, a bombing mission that destroys an enemy air defense site falls into both "force application" and "aerospace control" roles. Table 2 lists the roles, possible space missions, and the relevant core competencies. Further, the *Space Handbook* gives a detailed discussion of many of these space missions as related to these roles.[43]

Table 2. Roles and Missions for Space Power

ROLES	POSSIBLE SPACE-RELATED MISSIONS	RELEVANT CORE COMPETENCIES
Aerospace Control Space Control)	Counterspace Space Surveillance	Air and Space Superiority Information Superiority
Force Application	Strategic Attack Interdiction	Global Attack Precision Engagement Information Superiority
Force Enhancement	Surveillance and Reconnaissance Meteorological Satellite Systems Communications Satellites Navigation Systems Environmental Remote Sensing	Rapid Global Mobility
Force Support (Space Support)	Launch Support (Spacelift) On-Orbit Support	Agile Combat Support

As the various concepts for lasers in space are developed later in this report, they will be connected back to these roles and missions to help those who advocate space-based laser systems from either the technological or operational perspective. For example, active imaging of space objects from space platforms aids space control through the space surveillance mission. Laser propulsion systems could aid the spacelift mission in transferring payloads from LEO to GEO. It is clear that laser communication systems and space-based laser weapons aid the force enhancement and force application roles, respectively. The reason for putting the technical concepts into the proper roles and missions is to bridge the gap between the technological and operational worlds.

See Graphic.

The taxonomy developed here for space-based laser systems emphasizes the functional aspects of these systems, which helps relate the concepts to operational roles and missions as well as compare the concepts to existing systems and other non-laser alternatives. This taxonomy will be used in the following sections to discuss specific concepts for lasers in space.

V. PAST STRATEGIC PLANNING STUDIES

In recent years, a number of long range studies conducted by the Air Force are directly relevant to the use of lasers in space. The reason for looking ahead is that laser technology

is maturing and access to space is increasingly easy. At the same time, the end of the Cold War provides the opportunity for the senior leadership of the Air Force to search for the proper vision and strategy for the 21st century. In this section, various concepts for "lasers in space" are extracted from the more relevant strategic studies. It should be noted that some concepts that are being studied by NASA and the commercial sector are included in a final compilation of the concepts.

There undoubtedly are other planning documents, such as Mission Area Plans at AF Space Command, that contain concepts for using lasers in space. These strategic studies describe a reasonable number of concepts of space-based laser systems that fit in the four classes described earlier, and identify several high-payoff concepts with near-term technology demonstrations. The apparent consensus in these strategic studies is that the major concepts are known, but it is likely that some specific applications have been missed.

Laser Mission Study

Beginning at the end of 1991 and ending in October, 1992, a comprehensive study of laser applications to military missions, called the *Laser Mission Study (LMS)*, was conducted at the direction of Major General Robert R. Rankine and under the leadership of Lieutenant General Bruce K. Brown (USAF, then retired). The basic objective of the study was to "find applications that the operators could support."[44] A number of laser application studies were conducted in the past, but this more comprehensive study considered a wider variety of missions. There have been numerous technological advances, including the maturing of semiconductor lasers, the development of adaptive optics, and the integration of various technologies necessary for laser-based remote sensing. The *Laser Mission Study* objectives were:

- Unite users and technology developers in search for militarily useful laser applications, some as yet undiscovered, by (1) exposing users to laser technology and technologists to user missions and (2) identifying technology shortfalls or mission capability enhancements, considering the potential of laser technology
- Gain user understanding of, and support for, laser technology development
- Present game plan (methodology) for early injection of study results into S&T investment process[45]

More than 100 people from all four military services as well as other government agencies participated, including a specific "space panel" comprised of over 14 members from AF Space Command, Phillips Laboratory, program offices and support contractors. Of the 94 applications identified in the overall study, 22 made the final cut as concepts of high value to the operational community. Seven of these relate directly to space:

- Illuminator/Imager for Space Surveillance
- Ground-Based Laser ASAT Weapon
- Laser Satellite Communications/Mission Data Relay
- Weather Monitoring and Characterization
- Remote Earth Sensing and Characterization
- Space Debris Cataloging
- Space Track Accuracy Improvement[46]

Each of these seven concepts is discussed in some detail in the *LMS*, including a technical description, an operational concept, key enabling technologies, and technical challenges. These discussions are particularly useful for evaluating the concepts in *terms of technical feasibility and operational enhancement. The* LMS also includes a brief analysis of space-based active sensing for weather monitoring and remote sensing.

Additional concepts were identified by the space panel as "worth keeping in the database" and are included in the final compilation at the end of this section. However, the *Laser Mission Study* did not elaborate on these concepts because either the mission was of low interest to the operational users or the technology was not sufficiently mature. But most of the titles of the concepts are sufficiently descriptive to permit a first-order discussion.

New World Vistas

During the summer of 1995, the Air Force Scientific Advisory Board (SAB) was tasked by the Secretary of the Air Force and the Chief of Staff to "identify those technologies that will guarantee the air and space superiority of the United States in the 21st century."[47] The SAB undertook an intensive study that resulted in a 15 volume report called *New World Vistas (NWV)* that covers a wide range of technologies, including a host of concepts for lasers in space. (The *NWV* report consists of 14 unclassified volumes and one classified volume, including an ancillary volume of interviews and speeches related to *NWV*. All of the information discussed in this report related to *NWV* came from the unclassified volumes.) The SAB study team was composed of many leaders in the R&D area who collected information from AF laboratories, Department of Energy laboratories, operational AF organizations, and industry. While some of the ideas contained in *NWV* are evolutionary, some have revolutionary implications, there is a blend of technical and operational perspectives. And *NWV* is broader than the *LMS* given the greater breadth of the charter and the diversity of its participants.

Throughout the *NWV* report, lasers in space appear as concepts that will be of great value to the Air Force in the 21st century. The table at the end of this section consolidates these concepts. The *NWV* report discusses a number of weapons and non-weapons concepts for lasers in space, although the technical depth of the discussion varies from brief comments to extensive descriptions of systems. Not surprisingly, there is considerable overlap in the concepts between the *LMS* and *NWV*. Nevertheless, these two studies represent the best technical assessment of the strategic studies that include space-based laser concepts.

The Air Force scientific and technical community has taken the recommendations of the SAB as stated in the *New World Vistas* quite seriously. The senior leadership not only has redirected budgetary resources, but also is reorganizing the R&D laboratories into one AF research laboratory that will not report through the Product Centers as the four current laboratories do.[48] Anyone interested in understanding where the AF will be heading in the early 21st century is well advised to consider the *NWV* report in great detail. The weapon systems of tomorrow's air and space forces will emerge from the technologies that are examined in *NWV*.

Spacecast 2020

One strength of in-residence officer professional military education (PME) is giving a select group of officers the opportunity to focus their intellect and expertise on academic topics of interest to the Air Force, and to do so without the normal daily distractions. Thus, the Chief of Staff has used Air University (AU) on two recent occasions to study the effects of emerging technology on the future operational capabilities of the AF. The participants were primarily the students of Air War College (AWC) and Air Command and Staff College (ACSC), with oversight and contributions from the faculty. These studies typically have greater operational depth and less technical strength as compared to *NWV* and *LMS*. Though not intended as criticism, this distinction serves as a highly useful balance to the other reports. Since many AWC and ACSC students have operational experience, including combat in various recent engagements, they focus on what really works and what will be useful.

The first study, *Spacecast 2020*, resulted from a tasking from the AF Chief of Staff to "identify capabilities for the period of 2020 and beyond and the technologies to enable them"[49] that equate with US space superiority. The study uses an "alternate futures" approach to help the participants develop new concepts. Those concepts scored by an operational analysis and the highest scoring concepts were developed in a series of white papers. Scattered throughout the report are various concepts that involve lasers in space. While there is some overlap with the *LMS* and *NWV* concepts, the participants were less constrained by preconceived notions of technology and hence identified some concepts that stretch the limits of technology. For example, *Spacecast 2020* includes holographic projection from space, planetary defense weapons, and weather modification systems that would involve lasers in space in ways or at power levels that stagger the imagination. The table at the end of the section consolidates more important concepts for space-based lasers from *Spacecast 2020.*

Air Force 2025

The second AU contribution to strategic studies is the recently completed *Air Force 2025* study, which was directed by the AF Chief of Staff. The study was designed to be the capstone of a series of long-range studies that had been directed by the CSAF, including *NWV* and *Spacecast 2020*. The objective of *AF2025* was to address the question: "What capabilities should the USAF have in 2025 to help defend the nation?"[50] The study examined both technical ideas and operational concepts, soliciting worldwide input through the World Wide Web. The final product consists of 3,300 pages in ten volumes with 40 white papers that address a wide range of topics by focusing on innovative ideas rather than defining new roles and missions.

This study was undertaken just as *New World Vistas* was being completed. This timing allowed the *AF2025* participants (as with *Spacecast 2020*, composed of AWC and ACSC students and faculty) to interact with the *NWV* team. That overlap, however, meant that the AF2025 study did not benefit from a careful consideration of the ideas in *NWV*. The primary value of *AF2025* is the operational perspective brought by the officers in the study, even though a significant amount of technical detail is contained in some of the white papers.[51]

A number of concepts were generated, both internally and externally, and operations analyses were used to rank those concepts in terms of the competitive edge offered in

alternative scenarios. The best concepts were more fully developed into white papers. As with *Spacecast 2020*, the number of space-based laser concepts included in the study included varying amounts of technical detail. Most of the laser concepts involved high-energy laser weapons rather than the other three classes of laser systems. The laser concepts examined in *AF2025* are included at the end of the section.

NASA and Commercial Applications

The value of using lasers in space has been clear to the non-military users. The National Aeronautics and Space Administration (NASA) recently orbited a laser-based remote sensing experiment called LITE (that is described in more detail later). Both NASA and the commercial sector are interested in laser satellite communications for very-high data rates. Further, NASA is exploring the use of lasers for improved instrumentation onboard spacecraft, such as a deep space altimeter that uses laser pulses for accurate ranging off distant objects.

The International Society for Optical Engineering 1993 conference on "Space Guidance, Control and Tracking" examined technologies to improve spacecraft performance through enhanced attitude control.[52] For example, one of the concepts explored using a charged-coupled-device (CCD) detector to improve spatial acquisition and tracking for laser satellite communications. The interest of NASA and the commercial sector in technologies that enable space-based applications helps the military to be "smart buyers" in some of these technologies and to focus on areas that are militarily unique.

It is critical that DOD collaborate with NASA, the Department of Energy, and commercial companies in order to get the optimal use of dwindling R&D resources in the development of space-based laser applications. Although this type of cooperation is time-consuming and difficult, the payoffs should include improved interoperability, more rapid fielding of experiments, and improved understanding through data sharing. While all of the participants will benefit, the Air Force is best positioned to take the leadership through AF Space Command and the Phillips Laboratory.

Summary of Concepts from Strategic Studies

A variety of concepts discussed in the strategic studies use lasers positioned in space to accomplish various missions. In several concepts, the laser may be based on the ground and the beam sent to the intended target, possibly with the use of relay mirrors. The ground-based laser (GBL) ASAT weapon and power beaming from earth to space are examples of such concepts; these are also included in the table below for completeness because the beams transit the space environment. Table 3 is a compilation of the concepts grouped into the taxonomy described above. Additional concepts from other sources are included in the table to provide a comprehensive summary.

In the next section, a semi-quantitative scoring scheme is developed and then applied to the concepts listed in Table 3. In subsequent sections, a brief synopsis of each concept is presented as part of this scoring. The discussion briefly identifies the operational concept, operational enhancement, key enabling technologies, and primary challenges. (It is impossible in this report, due both to space limitations and the author's expertise, to cover all the concepts in depth.) Subsequent sections will focus on a few of the concepts that have

the greatest near-term potential and discuss ways to bring these concepts to fruition. The plethora of concepts and the emphasis given to space-based laser applications in the strategic studies strengthens the drive to put this technology into the operational community.

Table 3. Summary of Concepts from Strategic Studies

Concept	New World Vistas	Spacecast 2020	Air Force 2025	Laser Mission Study	Other Sources
ENABLING SYSTEMS					
target designation	X			X	
battlefield illumination	X			X	
guidance (alignment, docking)				X	SPIE
deep space laser altimeter					NASA
satellite-to-staellite velocimeter				X	
INFORMATION GATHERING SYSTEMS					
remote sensing for BDA				X	
environmental monitoring	X			X	
weather monitoring	X	X		X	
space derbis cataloging				X	
integrated Tactical Warnng/Attack Assessment				X	
active illuminator/imager for space surveillance	X	X	X	X	
INFORMATION RELAYING SYSTEMS					
sensor pointing accuracy beacon network				X	
sattelite traffic management/IFF				X	
laser communications and data relay	X		X	X	NASA
space track accuracy improvement				X	
space-based reference grid				X	
holographic projector		X			
ENERGY DELIVERY SYSTEMS					
laser rocket propulson	X			X	NASA
power beaming (earth to space)	X			X	
power beaming (space to earth, space to space)					NASA
space derbis clearing	X	X	X	X	
space-based counterforce weapon (a.k.a GPOW)	X	X	X	X	
space-based BMD weapon	X	X	X	X	
GBL ASAT weapon	X		X	X	

space-based ASAT weapon	X	X	X	X	
space-based counter-air weapon	X	X	X	X	
planetary defense weapon		X		X	
weather modification system		X		X	

VI. CRITERIA FOR EVALUATING THE CONCEPTS

A simple set of criteria that covers both technical and operational perspectives is used to rank the twenty-eight concepts identified in the previous section. Although somewhat qualitative, the assessment moves the discussion from purely descriptive reviews of concepts to critical evaluations of concepts that are most likely to strengthen operational capabilities in the near term. A five-point scoring system is used to evaluate proposals during a source selection and permit a semi-quantitative ranking of concepts.

Technical Criteria

Feasibility. This criterion measures whether the concept is theoretically possible by assessing the potential of the concept rather than its implementation. In some cases, the path to fielding a system is relatively straightforward even if the process has not proceeded very far, while in other cases, despite years of intensive study, significant challenges remain. In still other cases, the basic laws of physics may limit the likelihood that the concept will ever achieve fruition. The following five-point scale measures the technical feasibility of the concept:

1- concept unlikely to succeed, due to current understanding of basic laws of nature

2- multiple new breakthroughs required to make concept work

3- only a few major technical challenges or breakthroughs remain

4- no major breakthroughs required; multiple engineering issues remain

5- only minor technical issues remain to be resolved

Maturity. Technical maturity measures how far the concept has moved toward realization. The score assesses demonstrated progress in the process of developing the maturing of a concept, using the following five-point scale:

1- nothing has been demonstrated to support this concept

2- multiple major components remain to be demonstrated or developed

3- a few major components remain to be demonstrated or developed

4- major components exist but multiple, minor components remain to be developed

5- components exist; a complete system may have been demonstrated

Operational Criteria

Assuming that the concept would meet its technical objectives, the operational questions are whether the concept would substantially enhance operational capabilities, and whether the "cost" of the concept would prohibit the development or purchase of other military systems. The idea of enhancement and cost are distinct but related. A concept may be expensive in terms of funds and manpower but worth the investment if it adds unique capability. Although not addressed in detail here, there are alternative methods of achieving the same mission, many of which influence the assessment of new concepts.

Enhancement. This measurement qualitatively assesses how much the deployment of the proposed system would aid operational capabilities. In some cases, it adds a new way of operating that already exists, and thus provides an incremental improvement in capability. In other cases, the capability offered by a concept revolutionizes the operational capabilities, and thereby permits radical changes in the conduct of military operations. The following five-point scale assesses the enhancement of the various concepts:

1- limited enhancement; military requirement adequately met by existing systems

2- minimal improvement in military capability

3- some significant improvement, permitting increased flexibility or responsiveness

4- substantial new capability or greatly enhancing existing capability

5- revolutionary capability, giving decisive military edge to warfighter

Cost. Here, "cost" is meant to estimate the required funds and manpower in the current resource-constrained environment where procuring system A may mean system B will not be procured or modernized. These alternative costs are inherently subjective, because they are based on a prediction of which system delivers the most "bang for the buck." The following five-point scale measures the cost of the particular concept of a space-based laser system:

1- extremely expensive, requiring substantial delay or canceling of other systems

2- very expensive, requiring entirely new support system and multiple platforms

3- expensive, requiring a few platforms and using existing support system

4- inexpensive, using a single platform with multiple capabilities

5- relatively inexpensive, readily adaptable to existing systems

Although careful thought underlies the application of these criteria to the concepts described in the next sections, other evaluators might give different scores based on their knowledge of technology or operational requirements. There is no "correct" answer to this evaluation, rather it is a considered assessment. If the scoring motivates others to develop their own

ranking, then one of the objectives of this study will have been achieved.

Table 4. Scoring Criteria

Score	Description
	Technical Feasibility
1	concept unlikely to succeed, due to current understanding of basic laws of nature
2	multiple new breakthroughs required to make concept work
3	only a few major technical challenges or breakthroughs remain
4	no major breakthroughs required; multiple engineering issues remain
5	only minor technical issues remain to be resolved
	Technical Maturity
1	nothing has been demonstrated to support this concept
2	multiple major components remain to be demonstrated or developed
3	a few major components remain to be demonstrated or developed
4	major components exist but multiple, minor components remain to be developed
5	components exist; a complete system may have been demonstrated
	Operational Enhancement
1	limited enhancement; military requirement adequately met by existing systems
2	minimal improvement in military capability
3	some significant improvement, permitting increased flexibility or responsiveness
4	substantial new capability or greatly enhancing existing capability
5	revolutionary capability, giving decisive edge to warfighter

Operational Cost

1 extremely expensive, requiring substantial delay or canceling of other systems

2 very expensive, requiring entirely new support system and multiple platforms

3 expensive, requiring a few platforms and using existing support system

4 inexpensive, using a single platform with multiple capabilities

5 relatively inexpensive, readily adaptable to existing systems

VII. REVIEW AND SCORING OF CONCEPTS

In this section, we examine briefly each of the 28 concepts listed in Table 3 highlighting the operational concept, operational enhancement, key enabling technologies, and primary challenges. A detailed assessment is beyond the scope of this study and, in many concepts, references are given that more fully evaluate the technical and operational merits.

Based on the author's evaluation as well as other sources, scores are listed at the end of the discussion of each concept. Also, at the end of this section, Table 5 summarizes all the scores, including the total scores. The order of the listing of the concepts is the same as in Table 3 for continuity.

The first two concepts offer special advantages to the operational commands, meriting a more comprehensive development in the following two sections, in part because they hold little commercial potential. Space-based laser communication systems also offer great near-term potential and are being developed by DOD, NASA, and industry. The space-based remote sensing is another highly scored concept that has been investigated by NASA.

Space-based Laser Target Designator

Operational Concept. As part of the force enhancement mission area, the space-based laser target designator (SB-LTD) directly extends the current LTD systems.[53,54] A neodymium:YAG laser on-board a LEO satellite projects a beam onto a target on the earth's surface in order to give an aim point for a laser-guided weapon. The choice of the Nd:YAG laser is predetermined because this is the source that is used for all US LGWs. The system would likely include a moderately high-resolution imaging system and a video data link to an operator because safety and positive control of deadly force require human oversight. The operator could be located anywhere, including CONUS, an AWACS aircraft, or a theater of operations. The satellite would have to have a clear view of the target area as it passes overhead, meaning that weather, smoke or other obscurants could defeat the LTD, which is a constraint shared with current LTDs.

Operational Enhancement. Moving the LTD platform out of the theater eliminates the risk to the LTD operator. The LGW could also be released at a long range, eliminating risk to that platform as well. The appropriate LGW would probably be a powered munition, such as a cruise missile rather than a gravity bomb. The recent misses of cruise missiles during the DESERT STRIKE attacks against Iraqi air defense sites might have been reduced if a SB-LTD had provided aim points for the appropriate PGM. It is conceivable that the target could even be mobile and still be designated for destruction. Even a few SB-LTDs give a significant enhancement to the current capability for limited strikes and shows of force.

Key Enabling Technologies. Clearly a sufficiently powerful laser is needed. However, the 1.064 micron wavelength of the Nd:YAG propagates with low loss through the atmosphere, and diode lasers have been successful in pumping the neodymium, offering the possibility of an all-solid-state, electrically powered laser source with adequate power. The output optics would have to be large enough to keep a small enough spot on the ground for accurate weapons delivery. Calculations discussed in a later section suggest that a one-meter diameter output optical system, possibly consisting of a cassegrainian telescope, could suffice. The same optical system could be used for imaging the target area by sharing the aperture and using a high-resolution CCD array. A microwave communication system would be needed to send that image to a controller. Acquiring the target requires highly accurate position information of the SB-LTD as well as foreknowledge of the target's exact location. Given this information, computation could generate the required pointing vector to drive the imaging and laser systems. Pointing stability is critical, but could be satisfied by a recent advance in inertial reference units discussed in the next section.

Challenges. It would appear that most of the technology required for the SB-LTD is within reach. The primary challenges are operational. A large number of LEO satellites would be needed to give adequate coverage for sustained military operations. Opportunities of engagement need to be assessed with careful consideration of adverse weather obscuring the potential target areas. The cost of the individual satellites and the total system would be high.

Scoring. The concept was rated as part of the "virtual presence" paradigm by the *NWV* study as an interesting concept with high payoff, but they placed it in the long-term (30 year) development period, suggesting that they had concerns that the technology was not maturing soon.[55] The *Laser Mission Study* also seemed to make a similar assessment when it placed the SB-LTD concept in the "keep in the database" category.[56] There does not appear to be any fundamental principles that prohibit the concept from being developed, and the maturity of most of the technologies is high. The assessment of the two studies may not have considered the synergy of advances in pointing, imaging, diode-pumped lasers and high frequency microwave down-links. The acceptable cost of a small number of systems gives a unique capability for limited strikes.

Technical feasibility: 4. Technical maturity: 4. Operational enhancement: 5. Cost: 3. Total Score: 16

Battlefield Illuminator

Operational Concept. Offering potential for the force enhancement mission area, the concept is to project a laser beam over a large area on the earth's surface to aid existing low

light imaging systems in discerning targets.[57,58] There are already fielded laser illuminators to aid night vision devices (NVD) using semiconductor laser arrays such as gallium-arsenide (GaAs) lasers operating around 830 nm. Forward-looking infrared (FLIR) systems could be augmented by using CO_2 lasers operating at 10.6 microns. The illuminator could even be used to illuminate targets for infrared reconnaissance systems. The space-based battlefield illuminator (SB-BI) concept is a straightforward extension of the idea of using a flashlight to improve seeing in the dark, although, in this concept, the beam would be generated from a LEO satellite onto a target area. Because the illumination beam would likely pose no risk to ground personnel due to the large spot size, the illumination would not need a controller in the loop. The target location and the time of the illumination could be preprogrammed. Note that SB-LTD and the battlefield illuminator cannot share the same laser because the required wavelengths are different. The SB-LTD laser must operate at 1.064 microns because of LGW sensor requirements, while the SB-BI laser operates in the wavelength region of the imaging system that it is intended to enhance, which is typically the 800-900 nm region for NVDs and 8-12 microns for FLIR systems. A more detailed discussion of this concept is contained in Section IX.

Operational Enhancement. Applications include improved target acquisition from FLIR systems, augmented infiltration and exfiltration of special operations teams, enhanced landing under low light conditions, and increased effectiveness for night security of high value sites. Because the beam would likely be so large so that the energy density is at eye-safe levels, the illuminator could also be used for PSYOP missions. The friendly observer is less likely to be compromised because the illumination originates from a different location.

Key Enabling Technologies. A sufficiently powerful laser is required to provide enough illumination for the sensitivity of the fielded imaging systems. This levies a large requirement on the spacecraft power systems because of the inherent inefficiencies of lasers. (However, both semiconductor and carbon dioxide lasers are much more efficient than most lasers.) Highly accurate position information is required for both the satellite and the ground site to be illuminated to permit the pointing vector calculation for the laser beam. Highly precise pointing systems are required, but these are now available using advanced inertial reference units discussed in the next section. The output optical system needs to be large enough to permit the spot size on the earth to be as small as 100 meters in diameter. This should not be a limiting specification. It is possible the beam could be scanned over an area to expand the coverage, but this would significantly increase the system complexity.

Challenges. The principal challenge will be achieving the laser power requirements. Weather again will limit the opportunities for using the battlefield illuminator. By using more illumination satellites, limitations in coverage due to orbits could be reduced although at increased cost.

Scoring. There are no breakthroughs required, only engineering improvements in existing systems. A low number of systems could be deployed that would provide a significant capability for limited military operations. A moderate number of satellites would be required for larger scale theater operations or extended illumination of high value sites. The cost of the individual satellites would be moderately high due to the laser requirements.

Technical feasibility: 4. Technical maturity: 3. Operational enhancement: 5. Cost: 3. Total

Score: 15.

Alignment and Docking (Guidance Systems)

Operational Concept. The low divergence of many lasers provides a very narrow, straight beam that can be used as a guidance beam for this space support concept. The construction industry already uses He-Ne lasers for surveying and for active control of blade height on road grading equipment. The Laser Mission Study lists the concept of using lasers as a "space reference grid" without further development.[59] One realization of the concept could be to project three laser beams of different wavelengths from points around a docking port on a space station. By locating three optical detectors with wavelength filters at matching points on a space vehicle, the docking process could be automated. Using pulsed lasers, highly accurate range information could be obtained, further automating the docking process. Other approaches could use a laser homing beam and guidance system like that used on laser-guided munitions as they zero in on their target.

Operational Enhancement. By exploiting the pencil-like beam properties, the pulsed operation, and the monochromatic nature of the laser, autonomous guidance systems could be developed that greatly reduce the need for manpower-intensive, risky docking maneuvers. Refueling or re-supply of satellites would be more feasible with these types of guidance systems.

Key Enabling Technologies. Highly accurate position information would be required to get the two space vehicles relatively close. GPS signals could provide this capability if the spacecraft are able to receive the signals. This is not a major issue for LEO systems, but would be for MEO and GEO satellites. The laser power requirements could be met with current diode laser technology and the same semiconductor technology provides suitable detectors. The principal challenge would be the control algorithms to maneuver the vehicle along the guidance beams. Some of these schemes have already been worked out for terrestrial systems and could be readily adapted for spacecraft use.

Challenges. Initial acquisition of the guidance or homing beams may be an issue, although a low power radio-frequency beacon could be used for the coarse acquisition.

Scoring. Most of the components of this concept exist but have not been assembled in a space-qualified package. The guidance concept could be tested with airborne or underwater systems. The cost of the system should be low because of the availability of efficient semiconductor lasers. However, the operational enhancement is not overwhelming.

Technical feasibility: 5. Technical maturity: 4. Operational enhancement: 2. Cost: 5. Total Score: 16.

Deep Space Laser Altimeter

Operational Concept. This concept falls in the space support mission area of aiding on-orbit support. By sending laser pulses at an object with a reasonable reflectivity and then measuring the time between the transmission of a laser pulse and the time when the reflection is received back at the laser system, the distance from the object can be calculated with very high accuracy. The time-of-flight concept is the heart of the currently fielded

military laser range-finders. NASA has developed a deep-space laser altimeter based on this concept for use on the Near-Earth Asteroid Rendezvous (NEAR) spacecraft.[60] The NASA system should provide 2-meter accuracy. The package only weighs about 5 kilograms and consumes 15 Watts. The instrument should have an effective range of over 300 km. A useful instrument in itself, it also demonstrates that laser-based instruments are effective enabling systems in general.

Operational Enhancement. Accurate distance information is important for obstacle avoidance, determining orbital altitude, docking maneuvers, and landing operations. While military spacecraft are not expected to make interplanetary missions in the foreseeable future, there may be many applications for operations near the earth. Having a small, affordable, space-qualified package such as NASA has developed is a capability worth having "on the shelf" for future military spacecraft.

Scoring. The system already exists on the NEAR mission to a small asteroid. The immediate operational utility is low, but the concept of laser-based spacecraft instrumentation is important.

Technical feasibility: 5. Technical maturity: 5. Operational enhancement: 2. Cost: 4. Total Score: 16.

Satellite-to-Satellite Doppler Velocimeter

Operational Concept. Another laser-based spacecraft instrument is the Doppler velocimeter, aiding on-orbit operations as part of space support. The concept was considered in the Laser Mission Study but not ranked highly.[61] The concept relies on the narrow linewidth of the laser and the fact that EM radiation that reflects off a moving object undergoes a shift in frequency (or wavelength) that is proportional to the velocity. The small beam divergence permits precise pointing at the object of interest, which implies that highly accurate measurements of relative speeds are possible.

Operational Enhancement. Measuring closure rates is important to automated docking maneuvers. It is also an important measurement for determining the absolute speed of other satellites, assuming the speed of the laser platform is known. The absolute speed is a part of the data that allows prediction of where the satellite will be in the future, which is an important part of the AF's space track system.

Key Enabling Technologies. Ultra-stabilized laser systems provide the extremely narrow linewidth for the Doppler measurement. Suitable homodyne or heterodyne optical receivers are used to measure the Doppler shift and compute the relative speed. Accurate pointing systems based on inertial reference units and possibly GPS measurements permit placing the laser beam on the other satellite.

Challenges. Qualifying the existing laser Doppler measurement systems for space is the principal challenge as well as modifying these systems for the expected operational environment.

Scoring. Most of the components exist and the concept is well understood. The cost should be relatively low. However, the near-term military utility is probably low, as indicated by

the ranking in the Laser Mission Study.

Technical feasibility: 4. Technical maturity: 4. Operational enhancement: 2. Cost: 5. Total Score: 15.

SPACE-BASED LASER REMOTE SENSING CONCEPTS

Remote sensing is a fairly mature technology area used for many applications.[62] Space-based remote sensing, as part of the force enhancement mission area, has primarily used passive multi-spectral imaging to obtain information about terrestrial and near-surface locations. The false-color images taken from Landsat are a good example of using remote sensing for assessing crop and soil conditions on a global scale. The amount of data is substantial: 200 to 300 megabytes is required to store the digital data from one scene obtained with the 30 meter resolution thematic mapper on Landsat.[63] Thus, the value of remote sensing is just coming into its own as computer hardware and software are developed to manipulate the massive amount of data in a timely manner. Active remote sensing using synthetic aperture radar is being developed in order to get around weather limitations in imaging systems.[64] Radar penetrates light rain, haze, clouds, some tree canopies, and even the ground to shallow depths under the right circumstances. Lasers can also be used to gather information for remote sensing, with obvious military applications.[65] The new trend is to use lasers from space to gather information,[66] as the next three concepts illustrate.

Active remote sensing can use lasers to gather information about remote locations by projecting a laser beam onto the target site and then gathering the weakly back-scattered or reflected light. The amplitude, polarization, and frequency of the back-scattered light can all be used to measure properties at the remote location. The AF Phillips Laboratory Lasers and Imaging Directorate has expertise in the area of multi-spectral and hyper-spectral imaging for remote sensing, and is now pursuing some of the active sensing concepts described below, such as measuring wind speeds from orbit.

One approach, the differential absorption LIDAR (abbreviated as DIAL) system, sends two laser beams of different wavelengths through a region of air and looks for differences in absorption in the transmitted or back-scattered beams. Assuming the right wavelengths are used, DIAL systems can detect a wide variety of chemical compounds in the air. Some of the current DIAL systems are used to test for pollution. As shown in Figure 3, NASA has recently orbited a DIAL system, called the "Laser In-space Technology Experiment," or LITE, in Space Shuttle Mission STS-64 to test the concept.[67]

The experiment used Nd:YAG lasers with nonlinear optical crystals to provide output energies of 500 mJ for the fundamental (1064 nm) and frequency-doubled (532 nm) beams and 160 mJ for the frequency-tripled output operating at 355 nm. The laser generated short, Q-switched pulses at a prf of 10 Hz. A one meter telescope collected the back-scattered light, using photomultiplier detectors for the 355 nm and 532 nm returns and a silicon avalanche photodiode to detect the 1064 nm light. The LITE package successfully probed the atmosphere over Los Angeles to determine effluent levels.[68] It also measured the properties of clouds and aerosols in the stratosphere and troposphere.

The important point about the LITE experiment for this paper is that the technology currently exists and was successfully demonstrated in a space environment. The resolution and timeliness would not meet current military requirements, but the concept has moved to the engineering stage. Thus, the AF should aggressively pursue space-based laser remote sensing to provide new, highly useful information to the operator.

Figure 3. LITE As An Example of Space-Based LIDAR[69]

Remote Sensing for Battle Damage Assessment (BDA)

Operational Concept. The application for BDA would be to probe the atmosphere near a target site after it has been attacked to determine the effluents coming from the site.[70,71,72] In particular, chemical warfare agents, propellants, and other militarily-related compounds would be of greatest interest. Sensing biological agents is more difficult but conceivable. For the space-based concept, the DIAL system would be located on a LEO satellite that would have to be overhead just after the attack in order to be effective.

Operational Enhancement. Assessing the effectiveness of attacks is paramount for military operations in order to assign follow-on missions and to determine enemy capabilities. Also, in an era when chemical and biological warfare (CBW) agents are increasingly likely to be stored in bunkers that are attacked, being able to quickly determine if such agents have been released into the air is a highly useful technology.

Key Enabling Technologies. The proper laser wavelengths must be available, and the rapid emergence of tunable solid state lasers (as discussed in Section 3) that can be pumped by diode lasers should provide reliable sources of adequate power. Because the back-scattered signal is likely to be weak, a large optical receiver with highly-sensitive detectors would be required along with relatively powerful laser sources.[73] Rapid beam steering is needed to interrogate a large region of air as the satellite moves overhead. Advances in non-mechanical beam steering offer potential solutions.

Challenges. The receiver system is the most challenging technical issue. Having an adequate number of satellites to cover numerous target sites during an extended period of attack drives up the cost of a useful system, although even limited capability would be militarily useful given the high risk involved in unintentional dispersal of CBW agents. Clouds and haze will reduce the effectiveness of this concept.

Scoring. The Laser Mission Study team ranked remote sensing as a concept of high interest to the operational community. The feasibility and maturity of remote sensing is high with proven demonstration of a space-based DIAL system. However, finding the right wavelengths for substances of military interest may be a challenge.

Technical feasibility: 4. Technical maturity: 4. Operational enhancement: 5. Cost: 3. Total Score: 16.

Environmental Remote Sensing

Operational Concept. This concept is a generalization of the remote sensing concept just

discussed. Here, the space-based laser is used to interrogate a region of space or a target in order to determine some of its physical properties. A space-based laser system can help the Measurement and Signature Intelligence (MASINT) mission by measuring target properties. For example, the smoothness of the surface affects the polarization of the reflected beam and might provide a way of aiding target recognition.[74] The degree of reflectivity from a soil surface can estimate the moisture content, giving advanced warning of soft soil for the movement of heavy equipment such as tanks as well as troop movement.[75] For some of these concepts, a single frequency laser that can be polarized could suffice for some of the applications, avoiding the complexity of DIAL systems. However, tunable lasers would substantially extend the capabilities of this concept. The beam would be scanned over the target region, while a sensitive optical receiver processed the scattered laser light.

Operational Enhancement. The ability to gather greater information about a landing zone before inserting troops or equipment substantially increases global awareness. Searching a large area for distinctive signatures provides a new dimension to intelligence. Both of these applications, as well as other similar ideas, can be realized with a space-based remote sensing system.

Key Enabling Technologies. See the preceding concept for a discussion of critical technologies.

Challenges. See the preceding concept for some of the challenges of remote sensing. Here, specific wavelengths might be required for certain targets and suitable lasers of high enough power need to be developed.

Scoring. The technical challenge of target discrimination is greater than the effluent sensing of the preceding concept, lowering the technical scores. Also, the increased complexity of the system increases cost.

Technical feasibility: 4. Technical maturity: 3. Operational enhancement: 4. Cost: 3. Total Score: 14.

Weather Monitoring and Characterization

Operational Concept. This concept is another specialized application of the remote sensing discussed earlier for BDA. In this case, the space-based laser is used to measure meteorological parameters such as wind speed, cloud density, the height of cloud tops, water vapor content, temperature, and pressure.[76,77,78,79] Measuring time-of-flight for short laser pulses can measure cloud top heights and infer potential storms. Using a time-gated heterodyne optical receiver, the space-based weather monitoring system can measure Doppler shifts from a specific region of the atmosphere and thus compute the wind speed. The two examples highlight the potential of this concept. Currently, these measurements are measured at fixed points on the earth's surface, measured by weather balloons, or calculated by indirect, passive measurements from satellites.

Operational Enhancement. Direct measurement of winds over a target region can substantially improve the accuracy of unguided bombs, the insertion of airborne troops, and the operation of aircraft on unimproved airfields. More accurate measurement of atmospheric parameters extends the time interval for accurate weather prediction, which

clearly improves military operations.

Key Enabling Technologies. As already discussed, sufficient laser power and a highly sensitive optical receiver are required as well as accurate pointing and scanning systems. Selection of the proper wavelengths to optimally sense the various atmospheric parameters is a key technological investigation which could be met with tunable, infrared, solid-state lasers. On-board processing can fuse the large amount of collected data into information to reduce the communications bandwidth required. The weather monitoring and characterization systems could be sequentially developed, with direct measurement of winds being the most valuable initial objective due to the many military requirements for this data.

Challenges. Tunable lasers with moderate energy, such as the titanium:sapphire laser, would need to be developed and qualified for space operations. Also, fixed wavelength lasers such as holmium:YAG or thulium:YAG lasers are nearly ideal for sensing water vapor but need to be scaled to higher powers. Range-gated heterodyne optical receivers with high gain collecting telescopes are required. On-board, high-speed computers for data fusion would greatly enhance the system's utility. Other challenges for remote sensing systems were discussed in the previous two concepts.

Scoring. This concept was ranked as having "definite interest" by the *Laser Mission Study*. Substantial development has been done for near-earth wind sensing as well as ground-based LIDAR measurements for meteorology. However, the hardware for a complete space-based system is complex and requires some extensive engineering development. Even a relatively small number of satellites could give significant capability.

Technical feasibility: 4. Technical maturity: 3. Operational enhancement: 5. Cost: 3. Total Score: 15.

Space Debris Cataloging

Operational Concept. Space debris is an increasing problem due to the ever-growing number of defunct satellites, fragmented spacecraft, and spent rocket boosters. According to the *New World Vistas* study, there are about 300,000 pieces of debris, many in the LEO region.[80] Natural debris such as small meteorites and dust also orbit the earth. The potentially high relative velocity of the debris makes the impact of even small debris on orbiting systems very serious. Using its globally distributed Space Surveillance Network (SSN), the Air Force maintains an extensive catalog of space objects that includes debris. However, ground-based radar and optical systems can only measure objects larger than about 10 centimeters. A concept that received high ranking by the *Laser Mission Study* team and one that aids space control role via the space surveillance mission is to catalogue space debris with space-based laser surveillance systems that locate, track, and potentially identify a much greater amount of debris. This includes smaller objects in the 1 to 10 cm range that pose a high risk.[81] The concept could use one laser with a large beam divergence to obtain an optical reflection from the debris and a second, pulsed laser with small beam divergence (operating as a Doppler LIDAR) to measure the position and velocity of the debris. By varying the wavelength of the LIDAR, it might be possible to determine the composition of the debris or at least determine if it is natural or man-made debris. This information can be useful in removing the debris, a concept to be considered later.

Operational Enhancement. A more extensive knowledge of the debris field can be used to reduce the risk to operational spacecraft which have some maneuvering capability. The database can also be used to select orbits for new satellites that minimize the probability of collision.

Key Enabling Technologies. A relatively low number of satellites would be required if they could be designed for autonomous searching of different regions of the near-earth environment. A substantial on-board computer capability would be needed to process all the possible hits. The laser systems would likely consist of low power devices given the loss-free environment of space, but the optical receivers need to be very sensitive because the amount of reflected light from a small piece of debris would be low. Scanning systems would be needed to accurately point the laser beams. Because the search satellites might illuminate reconnaissance and early-warning satellites during its scans, the wavelengths for the lasers would need to be chosen to prevent damage to the sensitive optical receivers.

Challenges. The principal challenge will be in developing a sufficiently sensitive optical receiver in a reasonably small and affordable package. Recent advances in inertial pointing systems and non-mechanical beam steering should be exploited to develop a space-based "space debris cataloging" system.

Scoring. The operational need is high, and the technology should be attainable with a concerted engineering push, but the cost of a network of search satellites is likely substantial.

Technical feasibility: 3. Technical maturity: 3. Operational enhancement: 4. Cost: 2. Total Score: 12.

Integrated Tactical Warning and Attack Assessment

O*perational Concept.* The Integrated Tactical Warning and Attack Assessment (ITW/AA) concept links the data from multiple sensor systems to provide a rapid, near-real-time (NRT) determination of a launch of a theater missile launch and an accurate estimate of its trajectory and impact point. A potentially valuable part of the force enhancement mission area, the concept is listed in the *Laser Mission Study*, but it was not a high priority item and no details were given to suggest how the team conceived of using space-based lasers to augment the ITW/AA systems. However, as mentioned in the environmental remote sensing concept, a space-based laser radar could be used for automatic target recognition to identify transporter erector launchers (TEL) before the launch occurs and a SB-LTD could guide stand-off munitions onto the target. Space-based battlefield illuminators could also be used to increase the likelihood of detecting and tracking the missiles after they are launched as well as the warheads after they are deployed. Thus, the ITW/AA concept would combine a number of other space-based laser concepts.

Operational Enhancement. Space-based laser systems could provide improved detection of the threat and enhanced likelihood of negating the targets before launch or in the boost phase.

Key Enabling Technologies. See earlier discussion of the SB-LTD, SB-BI, and environmental remote sensing systems.

Challenges. See earlier discussion of the SB-LTD, SB-BI, and environmental remote sensing systems.

Scoring. The need to field multiple systems of the different types in order to provide adequate coverage increases the risk and complexity of this concept. The *LMS* ranking placed this concept of higher technical risk and lower operational relevance.

Technical feasibility: 2. Technical maturity: 2. Operational enhancement: 3. Cost: 2. Total Score: 9.

Active Illuminator/Imager for Space Surveillance

Operational Concept. Ground-based active imaging of space objects is a rapidly maturing technology at the AF's Starfire Optical Range (SOR) in New Mexico.[82,83] These experiments have developed laser imaging in an environment that requires adaptive optics to reduce atmospheric distortions. If the same imaging technology was placed on a spacecraft, the atmospheric effects are eliminated. If the range to the target can be reduced by manipulating orbital parameters, active imaging could be exploited to give three-dimensional images of the target satellite, its location and velocity data, and (possibly) MASINT data on the composition of the vehicle by assessing the reflectivity of the various surfaces. This concept supports space surveillance and the space control mission area.

Operational Enhancement. The space-based active imaging system would enhance the current space surveillance database, particularly in the area of space object identification. This increased awareness is an essential ingredient of effective space control.

K*ey Enabling Technologies.* Assuming the Starfire imaging technology can be utilized, the new requirements include highly accurate pointing systems that rely on recent developments in inertial reference units. The concept would also rely on active target acquisition systems using either microwave radar or large-divergence optical beams in order to provide coarse target location. Fine tracking would be accomplished through the high resolution imaging receiver, which is itself a stressing technology.

Challenges. The major challenges involve pushing the engineering limits of APT and imaging systems. The laser power could be kept reasonably low because of the loss-free environment of space.

Scoring. The packaging of the complex system makes this concept immature, but the underlying technology has been demonstrated by the SOR system.

Technical feasibility: 3. Technical maturity: 3. Operational enhancement: 3. Cost: 3. Total Score: 12.

Sensor Pointing Accuracy Beacon Network

Operational Concept. This is another concept identified in the *LMS* as a low priority concept but with no additional detail. However, it would likely aid force support for on-orbit operations or space control by improving space surveillance. Thus, it is not

possible to determine exactly what the study meant, but the title suggests using very low divergence laser beams broadcast from satellites of known position as a calibration system. By fixing the beams on the satellite to aim at the nadir (the point on the earth's surface that is directly below the satellite on a line that connects the satellite to the center of the earth), a ground optical sensor that intercepts the beam can use it as a reference to determine precisely where the sensor is pointing.

Operational Enhancement. Improvement in the pointing accuracy of ground sensors that are part of the Space Surveillance Network would generate more accurate position and velocity data on the numerous space objects in the database. However, other methods can be used, such as celestial objects and GPS, which makes the concept redundant.

Key Enabling Technologies. Relatively low-power lasers coupled with highly accurate pointing systems and highly stabilized alignment platforms would be required. Also, very accurate knowledge of where the satellite is located would be required; this data could be obtained from GPS for LEO satellites.

Challenges. The technical challenges appear to be small. However, the cost of deploying and operating a dedicated network of calibration satellites seems excessive given the added benefit. If the packages could be built as low weight, autonomous add-ons for other satellites, the concept would be more viable.

Technical feasibility: 4. Technical maturity: 3. Operational enhancement: 2. Cost: 2. Total Score: 11.

Satellite Traffic Management/IFF

Operational Concept. This is another concept identified in the *Laser Mission Study* as a low priority concept with no additional detail. It could aid either space control or space support mission areas. The concept of "identification-friend-or-foe" is a familiar one, and usually operates as a transponder that transmits identifying information. Applying this concept to spacecraft, a low power, large-divergence diode laser could be pulse-code-modulated with the identity of the spacecraft and other relevant information. Proper optical systems could make this transponder cover 360 degrees around the satellite. Power requirements would be modest due to the high efficiency of semiconductor lasers. An alternative concept would be to use a passive system that consists of a retro-reflector such as a corner cube or a "cat's eye" that is modulated (vibrated) so that it sends an encoded reflection back to any laser that illuminates it.

Operational Enhancement. As the near-earth space environment becomes more crowded and as spacecraft become more maneuverable, some sort of traffic management system similar to the current air traffic control system will likely be required. However, radio-frequency systems that already exist serve the same purpose, which suggests that the advantage of the laser system over these RF systems is not evident.

Key Enabling Technologies. High efficiency semiconductor lasers with PCM circuitry to send out the encoded signal as well as the broad-coverage output optical system would be needed.

Challenges. There are only a few pressing technical challenges, but the key challenge is establishing operational usefulness.

Technical feasibility: 4. Technical maturity: 1. Operational enhancement: 1. Cost: 5. Total Score: 11.

Laser Communications and Data Relay

Operational Concept. Transmitting information over a laser beam is a well-established concept, both using optical fiber and free-space pathways. Commercial fiber optic communication networks already handle tremendous volume for terrestrial telecommunications including voice, video, and data transmission. Free-space links are generally designed for short paths in areas where other communication networks are impractical.[84] There is a variety of methods for modulating the laser beam, including pulse code modulation (PCM), amplitude modulation (AM), frequency modulation (FM), and polarization modulation. Semiconductor diode lasers are ideally suited to this application because they operate by direct electrical-to-optical conversion, are highly efficient, and can be modulated at extremely high rates. Digital methods, like PCM, offer the best data rates with lowest error rates, but not all lasers can be modulated in this manner. Free-space links can also take advantage of the "wavelength division multiplexing" (WDM) concept used in fiber optical systems where different wavelengths are used as discrete channels for carrying information.

As a space support and force enhancement concept, space-based laser communication has been proposed by the *LMS, NWV,* and *AF2025* studies.[85] This concept also is actively being pursued by the AF Phillips and Rome laboratories as well as by NASA and the commercial sector. [86] The laser communication links can exist between satellites or between earth stations and the satellites, as shown in Figure 4. Different transmitter-receiver schemes and laser wavelengths may be better suited to the different type of links.

Figure 4. Schematic of Space-Based Optical Communication

McDonnell Douglas has developed technologies for space-to-space laser links for the Defense Support Program early warning satellites and a space-to-ocean link to communicate with submerged submarines.[87] The space-to-earth link could readily be aimed at an unmanned aerial vehicle (UAV) or C2 aircraft, such as the E-3A AWACS.

The Ballistic Missile Defense Organization (BMDO) is also active in developing space-based laser communications. It is funding efforts that would provide high-data-rate links from space capable of transferring 1.24 Gbps at distances up to 1800 km. This satellite laser communications package is scheduled to fly on the Space Technology Research Vehicle in 1998.[88] Thus, space-based laser communication systems are maturing rapidly.

Operational Enhancement. The ability to relay massive amounts of information is becoming a critical determinant of military success. The concept of global awareness, which relies on having dominant battlespace knowledge, is possible only if a steady stream of information reaches the operators, from the platoon leader in the field to the Joint Force

Commander in theater and the military support staffs in CONUS.

Laser communications offer a number of advantages over radio-frequency and microwave systems. First, the potential data rate is much higher because of the carrier frequency is much higher. The *NWV* study states that the data rate could exceed 10 billion bits per second (Gbps).[89] Second, the link can be more secure given the narrow laser beam. The implication is that someone would need to get inside the beam to intercept the message, interrupt the beam to the intended receiver, and thus signal that an intrusion had occurred. This fact also makes it very hard to jam laser communication links. Third, if the carrier wavelength operates outside the visible region, the communication would invisible, and thus covert, unless electro-optical systems are used to search for the beam. These last two advantages are captured in the notion of a Low Probability of Intercept/Low Probability of Detection (LPI/LPD) communication system. Fourth, because of the linearity of the atmosphere for low peak-power laser beams, there is no "cross-talk" between laser beams, reducing this source of signal degradation. Fifth, the laser communication system will be much smaller and lighter than comparable radio-based systems because the output "antenna" is much smaller, the laser is much smaller than microwave generators, and the power consumption is lower. These factors produce substantial savings in payload launch costs.

See Graphic.

Key Enabling Technologies. Acquisition of the receiving satellite in order to establish the communication link is a challenge in view of the small divergence of the laser beam. A higher divergence diode laser and a corner cube on the receiving satellite could solve this problem. Non-mechanical beam steering is desired to minimize spacecraft jitter. This technology is maturing rapidly for diode laser arrays, and sensitive detectors are required for receivers. Lasers with useful wavelengths, adequate output power, and the ability to modulate the output at the desired data rates are a key technology area that is developing rapidly without DOD involvement given interest in the commercial sector.

Challenges. The biggest challenge for space-to-space links appears to be the acquisition, pointing, and tracking problem. For earth-to-space links, the biggest problem is attenuation due to clouds, haze, or other atmospheric effects. For this reason, the *AF2025* study concluded: "Laser communication systems are a poor choice for communications between satellites and individual earth stations."[90] However, they noted that the use of spatially distributed ground stations that are linked by very high-speed communication lines could ameliorate this problem. Numerous minor engineering challenges remain in all sub-systems but steady progress is being made.

Scoring. This is one of the most promising space-based laser concepts and should be aggressively pursued by AF research laboratories and operational commands. The cost is likely to be high because it is an entirely new communication system.

Technical feasibility: 5. Technical maturity: 5. Operational enhancement: 5. Cost: 2. Total Score: 17.

Space Track Accuracy Improvement

Operational Concept. The concept of supporting space control through improved space surveillance was ranked by the *LMS* team as one of its top seven concepts, which was the subject of a mini-study to more fully develop the concept.[91] As described in *LMS*, the laser system would be a ground-based laser configured as a LIDAR to make highly precise measurements of satellite position and velocity. These state vectors would update the ephemeris information in the AFSPC Space Catalog database. An alternative configuration would be to use space-based lasers as described above for tracking space debris. The same data would be collected, with improved capability to measure the orbital characteristics of MEO and GEO satellites.

Operational Enhancement. A relatively small number of satellites could provide enough information over an extended period to augment the Space Surveillance Network. The improved ephemeris data reduces the risk of accidental collision, and permits better traffic management in determining orbits for new spacecraft.

Key Enabling Technologies. Moderately powerful, pulsed lasers are needed for detection and ranging. A number of infrared lasers are potential candidates. The wavelengths should be chosen to not interfere with any optical sensors on the illuminated satellites. Highly accurate pointing capability is required to acquire the satellites, assuming that the approximate position is known from other components of the tracking network. An autonomous target acquisition system could be developed using a large-divergence laser 'floodlight' and a highly sensitive detector to look for very weak reflections. The optical receivers must be sufficiently sensitive to measure weak returns of the satellites.

Challenges. The principal challenge will be in developing a sufficiently sensitive optical receiver in a reasonably small and affordable package. Another major challenge will be the pointing system. Recent advances in inertial pointing systems and non-mechanical beam steering should be exploited to meet the APT requirements of the space debris cataloging system.

Scoring. The operational requirement for improved accuracy in the Space Catalog is high and both the ground-based and space-based LIDARs offer feasible approaches to collecting the data.

Technical feasibility: 3. Technical maturity: 3. Operational enhancement: 4. Cost: 2. Total Score: 12.

Space-Based Reference Grid

Operational Concept. The straightness of a laser beam can be used as a reference grid or beacon, providing improved on-orbit operations for space support. Although the *LMS* only listed this concept by title because it did not rank high enough for further development, one possible realization of this concept would be an extension of the VOR and TACAN systems employed on earth for aircraft navigation. These systems broadcast signals that permit aircraft to determine the range and bearing to the navigation aid. A GEO satellite that sends laser beams with slightly different wavelengths or pulse encoding along different angles could serve a similar function. Another, smaller scale realization would be to use a grid of laser beams to maintain alignment of a distributed space vehicle like a large space antenna.[92] This version is similar to the guidance system discussed earlier. By placing

mirrors on the outer edges of the antenna and illuminating them with laser beams from the central hub, the reflections can be detected back at the central hub by detectors that generate a control signal to maintain the position of the antenna. Active alignment with a laser reference grid could also be used to hold multiple spacecraft into fixed relative positions, forming a large 'virtual' spacecraft. The *NWV* report discusses using distributed spacecraft constellations to give much wider coverage of the earth or much more accurate interrogation of the earth's surface with reduced cost, lowered time of deployment, and reduced vulnerability.[93] A laser reference grid could be used to hold this constellation together.

Operational Enhancement. The first concept of a navigation grid could improve the performance of maneuverable space vehicles that are likely in the next revolution in orbital operations. The second concept offers a method to increase the efficiency of single or multiple spacecraft in performing their mission.

Key Enabling Technologies. Pulsed lasers with low beam divergence are required to provide narrow beams. Sensitive detectors that can discern angular shifts in the incident signal, such as quad cell detectors, are needed to generate the control data. Computation of the control signals and the thrust generating systems are essential components of using the information relayed by the laser reference grid.

Challenges. Numerous engineering challenges exist to make the various possible applications of laser reference grids come to fruition. The specific challenges depend on the application.

Scoring. The need for reference grids is predicated on significant advances in other spacecraft, which suggests that it is unlikely to be needed in the near future.

Technical feasibility: 3. Technical maturity: 2. Operational enhancement: 3. Cost: 2. Total Score: 10.

Holographic Projector

Operational Concept. This concept, which would fall into the force enhancement mission area, was considered in the *Spacecast 2020* study, and as a truly novel idea provides evidence that the strategic studies did consider "out of the box" ideas. However, the concept ignores the fundamental physics of generating holograms. The concept is a "system that could project holograms from space onto the ground, in the sky, or on the ocean anywhere in the theater of conflict for special operations deception missions. This system would be composed of either orbiting holographic projectors or relay satellites that would pass data and instructions to a remotely piloted vehicle or aircraft that would then generate and project the holographic image."[94] The apparent intention is to generate three-dimensional images of sufficient quality to make the observer believe an actual object is being seen. For example, projecting the face of Allah over Baghdad has been mentioned as one application of this concept for PSYOP missions; projecting the image of a tank would be a deception mission that could force enemy troops to move out of their position, exposing themselves to attack. There have even been suggestions by anonymous sources that these holographic images could be made to produce speech as well, which is theoretically possible using the photo-acoustic effect in air. This effect has been proposed by Oak Ridge National Laboratory for a laser-based emergency broadcast system.[95]

Operational Enhancement. If this concept were achievable, there would be great operational enhancement. There would be a tremendous "dual-use" benefit to the entertainment industry if the technology were releasable.

Key Enabling Technologies. A hologram is basically an interference pattern that has been recorded in some medium, such as film or a nonlinear crystal. The pattern is generated by overlapping a laser reference beam that has a very smooth phase front with a laser beam that has been scattered off the object to be imaged. The two beams interfere, creating bright and dark regions that, when reilluminated with a suitable optical source, recreate the image to an observer who looks at the hologram from the right point of view. Ideally, a laser is used to view the hologram, although "white light holograms" produce fairly good images using regular incandescent bulbs. The key technologies here are finding some way to generate the interference pattern in air and then illuminate that pattern with a visible laser beam, or possibly sunlight if the angle is correct, to create the image for the intended observers. Modulating the interference pattern would be required to create the illusion of motion.

Challenges. The ability to create holographic images is well established, but creating them in an uncontrolled environment like the open air is almost inconceivable. Making images that are realistic enough to confuse an enemy is highly unlikely in the next 30 years. The ancillary concept of auditory project, however, is feasible and demonstrated, but probably would not be done from a space-based platform given the difficulty of controlling the region of air that is modulated.

Scoring. Even the *Spacecast 2020* study ranked this idea as "so far in the future" that it is not worth further consideration.

Technical feasibility: 1. Technical maturity: 1. Operational enhancement: 5. Cost: 1. Total Score: 8.

Laser Rocket Propulsion

Operational Concept. Using laser beams to generate propulsion is another concept identified in the *Laser Mission Study*, but was ranked low and was not described further.[96] If successful, it would aid the space support mission area by giving alternatives for spacelift. The concept has been investigated by NASA, the Department of Energy and the Air Force. As described by Muolo,

[T]he basic scheme involves transmitting laser energy from some platform (ground, airborne, or orbiting) through an optical window to heat a working fluid. This fluid could be hydrogen, perhaps seeded with cesium or carbon to improve energy absorption. Very high temperatures and high I_{sp} [specific impulse] (over 1,000 seconds) would be possible.[97]

The *New World Vistas* study also mentions generating thrust by sending energy to the spacecraft via a high power laser beam.[98] They indicate that both electric propulsion and hot hydrogen gas propulsion engines could be driven by off-board laser energy, significantly decreasing the weight of the vehicle. Such engines have low thrust, making them most appropriate for orbital transfer.

Lawrence Livermore National Laboratory (LLNL) has investigated an alternate approach to laser propulsion that would work in both the atmosphere and in space. LLNL conducted tests "in which a laser beam was directed at a pusher plate with machined paraboloid dimples. Light was focused by each dimple on a spot behind the plate. The focused beam heated air pockets and the expanding pockets imparted a thrust to the plate. This concept provides respectable thrust in the atmosphere. In space (vacuum) the dimpled plate is jettisoned to expose a block of solid propellant which is ablated by the laser beam to produce thrust."[99]

The Phillips Laboratory recently conducted experiments that support the concept of power beaming for propulsion, projecting that "chemical rocket engines can be replaced by lightweight, efficient ion or atomic propulsion engines powered by thermal or electrical energy produced from a ground-based laser."[100] In partnership with NASA, the Department of Energy's Sandia National Laboratory and the COMSAT Corporation, Phillips Laboratory personnel used the 1.5 meter telescope at the Starfire Optical Range to transmit a laser beam over 3 million kilometers onto the Galileo spacecraft, demonstrating both the concept and a pointing accuracy sufficient to place the 40 microradian beam on the target.

Operational Enhancement. Reducing payload weight decreases the launch costs, or, conversely, the weight saved by the laser propulsion engine can be used for increases in productive payload. A Phillips Laboratory report suggested a 50 percent reduction in launch weight of geosynchronous satellites is possible using laser propulsion.[101]

Key Enabling Technologies. Efficient high-energy lasers are critical to this concept. Also, designing the engine requires windows with high transmission and gases that have high absorption for the laser wavelength, under the current concept.

C*hallenges.* The laser source is most likely to be ground-based for any near-term applications due to difficulties in packaging a high-energy laser into a spacecraft. However, ground-based lasers face substantial propagation challenges in getting the laser energy up to the spacecraft. Some concepts such as solar-pumped chemical lasers may alter this bias in ten years or more, permitting space-based HELs to drive laser propulsion engines..

Scoring.

Technical feasibility: 2. Technical maturity: 2. Operational enhancement: 3. Cost: 2. Total Score: 9.

Power Beaming (Earth-to-Space)

Operational Concept. This concept falls in the space support mission area of on-orbit support. Providing energy on-board a spacecraft has long been a major challenge because it consumes a significant amount of space and weight. Various methods of producing electricity are used, including photovoltaic (e.g., solar panels), electrochemical (e.g., batteries and fuel cells) and thermoelectric (e.g., solar-thermal conversion, nuclear reactors) systems.[102] The concept of using a ground-based laser to beam power up to a satellite has been considered by a number of sources, including *LMS* and *NWV*.[103] The ground-based laser system can be a large facility that has access to the abundant energy of terrestrial

sources. The energy in the laser beam is collected on the spacecraft and converted into energy either directly by using a photoelectric process, or indirectly by heating up a substance. That substance then generates electricity or by driving a chemical reaction that stores the energy in the reaction products that can be later used in a fuel cell or battery. Other conversions of light to energy should be considered to identify the most efficient method. The key advantage is that the small beam divergence of the laser beam means that most of the energy can be collected by a relatively small telescope on the satellite.

Operational Enhancement. Increased lifetime of spacecraft, decreased total weight for the same mission payloads, and increased mission payload for the same total weight are some of the potential operational enhancements. One application would be to recharge a spacecraft while it is in the shadow of the earth and cannot receive solar energy. For some orbits, this could substantially reduce payload weight by decreasing the need for on-board energy sources.

Key Enabling Technologies. For ground-based laser power beaming, compensation for atmospheric distortions is critical for efficient delivery to the spacecraft. The research at the AF Starfire Optical Range has matured this technology. Also, high efficiency collectors are required on the satellite, with photoelectric or photothermoelectric being the most promising concepts. These collectors must be able to handle large amounts of power without being damaged. Stabilized platforms with sub-microradian accuracy are needed on both the ground and space systems to insure the laser beam hits the right part of the satellite to avoid damaging the satellite and to improve the efficiency of the power transfer.

Challenges. The inefficiencies and high cost of ground-based lasers is a major challenge. Also, clouds and haze can attenuate or totally block the beam, requiring that the laser be located where clear weather is prevalent most of the time or that multiple sites be constructed.

Scoring. The concept is feasible but both laser and collector technologies are immature. Operational enhancement is likely but limited because of the mature state of current power generation systems. Future systems would have to be specifically designed to benefit from laser power beaming.

Technical feasibility: 2. Technical maturity: 2. Operational enhancement: 3. Cost: 2. Total Score: 9.

Power Beaming (Space-to-Space, Space-to-Earth)

Operational Concept. Similar to the concept above, the space-to-space power beaming would fall in the space support area while the space-to-earth power beaming would lie in the force enhancement mission area. This concept beams energy from a space-based laser to either another satellite or down to the earth, as mentioned in *NWV*.[104] The advantage for space-to-space power beaming is avoiding atmospheric distortion and losses as well as weather-related mission cancellation. The range between the satellites may also be less than from earth to the receiving satellite, and thus reduce the power requirements on the laser source. Beaming power from space to earth offers the possibility of providing significant amounts of power at remote sites where other sources of energy are not readily available, such as unattended ground sensors. Also, the atmospheric effects appear to be less for lasers

pointing down into the atmosphere, in part because there is less remaining path length when the beam enters the more dense regions. Although this prospect needs further modelling, it is clear that power-beaming from earth-to-space is not the same as from space-to-earth due to the asymmetry of the atmosphere. Also, electrically-powered, high-altitude UAVs could be recharged by space-based lasers. These UAVs could provide communication links, tactical surveillance, theater missile defense, and temporary navigation aids.

Operational Enhancement. As before, by reducing the requirements to carry energy-generating and energy-storing equipment, the cost, size and weight of the satellites and terrestrial equipment powered by the laser power beaming could be reduced.

Key Enabling Technologies. Compact, high-energy lasers of suitable wavelengths and long operational lifetimes are required. Carbon dioxide lasers are a possible candidate due to the high efficiency (about 30 percent), as are solar-powered atomic bromine lasers. The *AF2025* study recommended considering solar-powered lasers for the various HEL missions.[105] A critical part of this concept is providing the power to the laser for the beaming. Solar energy and a nuclear reactor are viable candidates. As mentioned in the previous concept, high efficiency, durable power collectors and accurate pointing systems are needed as well.

Challenges. The principal challenge for this variant of power-beaming is the laser source and its associated systems.

Scoring. Although the concept appears feasible, most of the components remain to be developed. The enhancement resulting from space-to-ground power beaming could be significant.

Technical feasibility: 2. Technical maturity: 2. Operational enhancement: 4. Cost: 2. Total Score: 10.

Space Debris Clearing

Operational Concept. As discussed earlier, space debris is a growing threat to space operations. High-energy lasers offer the possibility of removing the debris. Although the *NWV* study specifically suggests using a ground-based laser for clearing space debris,[106] basing the laser in space may offer better angles from which to irradiate the debris. The concept, supporting the space control and space support areas, would be to project a laser beam from a space-based, pulsed HEL and vaporize a portion of the surface of the debris, creating a small burst of thrust from the blow-off of material. By repeatedly hitting the debris, sufficient impulse could be transferred to cause the debris to de-orbit, and burn up in the atmosphere. Tens to hundreds of pulses may be necessary. Obviously, a great deal of care must be taken to insure the thrust slows down the debris, which would cause it to move to a lower orbit, and that the lower orbit does not result in a collision with any other space objects. Even a collision with other debris should be avoided as it would likely generate more pieces of debris that are smaller and more difficult to track. This concept could be merged with the space debris identification concept, using the laser operating at low power for detection and at high power for debris removal.

Operational Enhancement. There is currently no method to clear the debris from space. A

space-based laser offers one of the few viable options to remove the threat. With greatly increased emphasis on exploiting space for future AF operations, this concept may be well worth the substantial investment required.

Key Enabling Technologies. A high-energy, pulsed laser with a long operational life is required. Open-cycle chemical lasers would not be good choices. Current technology offers a number of candidate lasers that can produce tens of kilojoule pulse energies that would be sufficient for the mission, if the output optics are large enough to focus the beam in a small spot on the debris. For example, a self-contained, two kilowatt, master oscillator-power amplifier (MOPA), Nd:YAG system (called "MODS" for Mobile Ordnance Disposal System) has been built for anti-landmine missions that fits in a tracked vehicle. Also, electrically pumped, closed cycle, carbon dioxide lasers are a mature technology used for industrial welding. Large, lightweight optics would clearly be required. Accurate pointing of the laser beam is an additional requirement that can be met with current technology.

Challenges. The large-scale optics may be the most pressing technology for this concept. Also, the orbital mechanics calculations pose a significant challenge in determining when to apply the laser pulses.

Scoring.

Technical feasibility: 3. Technical maturity: 2. Operational enhancement: 4. Cost: 3. Total Score: 12.

SPACE-BASED LASER WEAPONS CONCEPTS

The next five concepts envision using the laser in direct, offensive roles against adversarial targets, while the sixth concept targets extraterrestrial objects. All these concepts fall in the space control and force application mission areas. The seventh concept, falling more into the force enhancement area, aims the high power beams from space back at the earth to alter weather patterns. Space-based laser weapons (abbreviated here as SBL with the assumption that it refers to an HEL weapon) have been studied extensively over the past twenty years and numerous references describe the technology from favorable,[107,108] neutral,[109] and unfavorable[110] perspectives. Scientists and engineers have been diligently pursuing the dream of high-energy laser weapons for over thirty years[111] and their efforts are paying off in maturing technology. The high power Alpha laser developed by TRW is a good example of their success, as reflected in renewed congressional funding.[112]

Obviously, the next few pages cannot give a thorough summary of this complex topic, but the generalizations below should give a fairly accurate appraisal of these seven concepts. Most of the concepts are variants of the SBL weapon concept, with the exception of the GBL ASAT concept where the laser is based on the ground. This concept is included (1) for comparison to SBLs and (2) because the GBL beam may be bounced off relay mirror satellites to accomplish its mission. Some of the relay mirror challenges overlap with some of the technological challenges for SBLs.

A few general comments should be made about laser weapons. There is no doubt that a high-energy laser can cause substantial damage to a target, as is routinely done with laser

welders for industrial applications and medical lasers for a wide variety of surgeries. Damage of militarily significant targets has been demonstrated with the destruction of air-to-air missiles with the Airborne Laser Laboratory and a pressurized booster tank with the MIRACL laser. The key advantages of a laser weapon is the speed-of-light, straight-line delivery of the energy with little concern about windage and ballistic effects, as discussed in an earlier section. However, laser weapons are inherently inefficient ways of destroying targets. The production of the laser energy is usually difficult, with single-digit efficiencies common for high-energy systems such as the Alpha laser and MIRACL systems. The coupling the energy to the target usually occurs at the surface where the light is absorbed, unlike the deep penetration common to kinetic energy systems like bullets. Thus, it may be difficult to kill some targets like reentry vehicles and it may be easy to develop countermeasures such as thicker skins or spinning the target to dissipate the laser energy. CW lasers need to dwell on the target for a sufficient time to damage it by thermal effects, while pulsed lasers damage the target by blowing off part of the surface, causing a plasma. This plasma becomes an absorbing surface itself, so the laser energy may end up heating the blown-off material rather than further damaging the target. All of these challenges are well known to the laser weapon community and a number of innovative solutions have been found. There is great value in pursuing laser weapons because they will offer a capability that is not available in any other weapon system. However, this brief discussion highlights the fact that this pursuit is a very challenging one.

Space-Based Counterforce Weapon

Operational Concept. This concept is an overarching term that applies to any application of SBLs against military targets such as military satellites, nuclear warhead reentry vehicles (RV), missiles in the boost phase, high-flying military aircraft, and anti-satellite kinetic energy missiles. The term was used in the *LMS*[113] but was also discussed in *Spacecast 2020*[114] and *AF2025*[115]. The *NWV* report discusses a similar concept that they called the Global Precision Optical Weapon (GPOW) that would have a "clearly dominant role in warfare."[116] Carryovers from the Cold War, the term "counterforce" is juxtaposed against "countervalue" used to describe targets that are usually predominantly civilian such as cities. Treaties such as the Anti-Ballistic Missile Treaty restrict placing operational ABM systems in space and may affect other SBL applications.

Operational Enhancement. The capability to negate adversarial targets at great distances at the speed-of-light would be a revolutionary capability and has served as the motivation behind decades and billions of dollars of research. HELs are one of the few technologies with the potential of destroying ballistic missiles in the boost phase. Even a limited number of SBLs offer significant capability for a limited number of ballistic missile launches that might characterize a terrorist or rogue-state attack against the United States or the limited number of theater missile attacks during a conflict like the Gulf War. The *Spacecast 2020* study proposed the idea, echoed in *AF2025*, of using the SBL for a range of missions such as passive imaging using the large telescope by itself and active imaging using the laser operating at low power.[117]

Key Enabling Technologies. High-energy lasers are the obvious central technology for this concept. Most of the contemplated designs use CW chemical lasers that would destroy their targets by thermal effects. The hydrogen fluoride laser operating at 2.7 microns is the most

mature candidate. Large diameter (>10 meters), lightweight mirrors are required in order to focus the laser beam on the target. Near-real-time target acquisition is required, perhaps by linking the SBL to early warning satellites. The pointing and tracking systems must also be robust. The interval between launch of a ballistic missile and the end of the boost phase can be as short as 60 seconds, levying a requirement for automated battle management software. The ability to rapidly slew the beam to a new target is a key requirement for engaging multiple targets. *NWV* discusses their view of the technical requirements for the GPOW in some detail.[118]

Challenges. Each of the SBL systems (e.g., laser device, large output optics, APT, battle management software) has significant engineering challenges to overcome. The SBLs are very expensive systems and could be attacked by anti-satellite weapons such as the Soviet co-orbital interceptor developed in the late 1970's. Thus, a defensive system would also be required for space-based battle station. This system could use either kinetic or directed energy weapons to counter the ASAT weapon.

Scoring. While scoring a general concept is difficult and less meaningful than considering the specific concepts discussed below, the overall concept is feasible but faces monumental engineering challenges. The operational enhancement would have strategic implications for national missile defense as well as provide a force multiplier for theater operations. However, deploying even a limited number of SBLs would be very expensive.

Technical feasibility: 3. Technical maturity: 2. Operational enhancement: 5. Cost: 1. Total Score: 11.

Space-Based Ballistic Missile Defense (BMD) Weapon

Operational Concept. Already in the research phase but given a significant impetus by President Reagan's speech on March 23, 1983, the idea of building an effective defensive shield against a massive ICBM attack included the use of space-based lasers to destroy the boosters before the reentry vehicles were released. The laser beam would be directed at the side of the booster, weakening it by heating and letting the internal pressures rupture the booster. The RVs are much harder targets because they are covered with an ablative cover capable of sustaining the heat of reentry. A large number of SBLs would be needed to provide an effective defense due to the orbital movement of the systems (likely to be deployed at about 1300 km with an orbital period of a little less than two hours[119]) and the large number of boosters that an adversary with ICBMs might launch.

Operational Enhancement. Destroying the boosters in the boost phase is the best solution because (1) the booster is the softest link in the chain of events that send the nuclear warheads to the target, and (2) the warheads and other debris falls back on the launching nation. An effective SBL BMD system would provide a unique, highly valuable capability to the warfighter and the nation.

Key Enabling Technologies. The discussion in the previous concept applies here. A significant amount of R&D has resulted in proof-of-concept demonstrations of the Alpha hydrogen fluoride laser, the Large Advanced Mirror Program (LAMP) and the Large Optics Demonstration Experiment (LODE) beam control system. The Ballistic Missile Defense Office (BMDO) is continuing the SBL development with the Alpha/LAMP Integration

(ALI) program.

Challenges. Again, the discussion in the SBL Counterforce concept applies to this concept. The systems management challenges are significant. There must be an autonomous system that would detect the launch, activate the SBL, acquire and track the target, point the laser at the target, engage the target with the laser for a sufficient time to destroy it, and then rapidly move to the next target. The complexity and brevity of the engagement has been studied in great detail by the battle management portion of the SDIO program. Also, the laser propagation and target interaction issues are as important as the challenges of making very high-energy laser devices.

Scoring. This is perhaps the most challenging and important mission for an SBL.

Technical feasibility: 3. Technical maturity: 3. Operational enhancement: 5. Cost: 1. Total Score: 12.

Ground-Based Laser Anti-Satellite (ASAT) Weapon

Operational Concept. The GBL ASAT is included (1) for comparison to SBLs and (2) because the GBL beam may be bounced off relay mirror satellites to accomplish its mission, with the relay mirror satellites having some of the same technological challenges for SBLs. Having some potential for BMD through the use of relay mirrors, the GBL ASAT system could disable satellites at lower powers than that required for the BMD mission because satellites are softer targets and the ranges are much shorter. According to *NWV*, satellites are "particularly vulnerable to laser attack...Target irradiances of several to ten watts/cm^2 are adequately lethal."[120] The GBL ASAT weapon would likely be located at a low latitude site that has exceptionally clear weather most of the year so that it could attack satellites when they pass overhead. The concept is proposed in both *NWV* and *AF2025* studies.[121]

Operational Enhancement. Having a non-nuclear capability to deny adversarial satellites would provide a critical force enhancement tool for space control.

Key Enabling Technologies. Projecting a high power laser beam from the ground requires a high power laser, large telescopes, atmospheric compensation, high accuracy pointing and tracking systems, and imaging systems for kill assessment. Because the laser does not have to be compact and can access the local power grid or other substantial energy sources, the GBL is more readily developed than the SBL ASAT weapon. Candidate lasers would include the COIL operating at 1.315 microns that has relatively good transmission through the atmosphere. High average power Nd:YAG systems operating at 1.064 microns are also feasible.

Challenges. Most of the technologies for a GBL ASAT are maturing. Only moderate engineering challenges remain to provide a limited capability. However, operational issues over where to base the systems and how to employ them remain. Significant political issues are likely to arise with the ASAT mission because attacking a nation's satellites would likely be taken as a military attack on the nation.[122]

Scoring. The GBL ASAT is a relatively mature concept aimed at relatively soft targets.

Technical feasibility: 4. Technical maturity: 4. Operational enhancement: 5. Cost: 2. Total Score: 15.

Space-Based Anti-Satellite (ASAT) Weapon

Operational Concept. The same operational concept described for the GBL ASAT would be the basis for the SBL ASAT, except that that laser would be placed on an MEO orbiting platform. The relative softness of the satellites, the lack of any atmospheric effects and the decreased range at the time of engagement reduce the power requirements for the SBL ASAT system as compared to the BMD mission.

Operational Enhancement. The operational enhancement is the same as that provided by the GBL ASAT weapon.

Key Enabling Technologies. Developing a high power, lightweight, reliable laser device with a 'deep magazine' is the critical technology but the large, lightweight optical elements are also crucial. The APT system requirements are similar to those discussed in many of the preceding concepts.

Challenges. The placement of a SBL ASAT in orbit would likely raise serious international issues and may be restricted by the Outer Space Treaty of 1967. Significant technical issues also remain as discussed for the SBL Counterforce concept.

Scoring.

Technical feasibility: 3. Technical maturity: 3. Operational enhancement: 5. Cost: 2. Total Score: 13.

Space-Based Counter-Air Weapon

Operational Concept. The SBL could be used to attack high-flying aircraft (above 30,000 feet or so) because high power lasers can penetrate to that altitude with relatively little loss of energy, even if the wavelength is one that is strongly absorbed at lower altitudes. In fact, having the wavelength stopped by the lower air layer provides the requisite laser safety for unintentional illumination of targets. (If the wavelength is not strongly absorbed, it would be conceivable to attack soft targets on the surface.[123]) The hostile aircraft could be tracked either from the SBL via infrared or radar techniques or by an off-board sensor and the location relayed to the SBL. With sufficiently large optics, the beam could be focused to a small enough spot to cause structural failure at critical parts of the aircraft. The size of the optics and the power of the laser should be significantly lower than that required to destroy an ICBM because the aircraft's slower speed permits longer dwell times.

Operational Enhancement. The capability of attacking aircraft without putting friendly forces at risk and in regions where anti-aircraft weapons are not available would be a significant force enhancement and contribute to air and space superiority. General Fogleman's goal to "find, fix...and target anything that moves on [or near] the surface of the earth" referenced in the opening paragraphs of this study would be greatly aided by SBL counter-air weapons.

Key Enabling Technologies. Because this concept is akin to the SBL BMD, the key technologies include the laser device, large, lightweight optics, APT systems, and self-defense systems.

Challenges. Although significant challenges remain in each technology area, the power requirements for the laser and the size of the optics would likely be somewhat lower than those of the SBL BMD weapon.

Scoring.

Technical feasibility: 3. Technical maturity: 3. Operational enhancement: 5. Cost: 1. Total Score: 12.

Planetary Defense Weapon

Operational Concept. The threat of an asteroid or large meteor colliding with the earth is remote but not impossible. The results of such a collision would be cataclysmic, delivering the energy of hundreds to thousands of megatons of energy and possibly destroying life on the earth. At present, we may have the rudiments of a space surveillance system that could warn us of the impending collision but we lack any technology to counter the threat. In the *Spacecast 2020* study, the team considered an asteroid negation system that could include directed energy weapons such as lasers.[124] The idea discussed in clearing space debris, of creating multiple, cumulative thrusts via laser ablation, could be applied to the asteroid to change its direction slightly, causing it to miss the earth. The momentum of even a small asteroid is very large, making any attempts to alter its trajectory challenging. Engaging the target at extremely long ranges would give the best opportunity to affect its path, but that imposes demanding requirements on the laser system.

Operational Enhancement. No operational requirement exists for this mission, although it would clearly be in mankind's interest to prevent such a disaster.

Key Enabling Technologies. Extremely powerful lasers would be required for this concept, possibly requiring multiple HELs or lunar-based lasers.

Challenges. The challenges are so imposing that the *Spacecast 2020* operational analysis team did not consider the concept further.

Scoring.

Technical feasibility: 2. Technical maturity: 1. Operational enhancement: 1. Cost: 1. TOTAL COST: 5.

Weather Modification System

Operational Concept. A concept proposed by *Spacecast 2020* and echoed by *AF2025* is the notion of modifying the weather using a directed energy source such as HPM and HEL systems.[125] The concept is to deliver enough energy to a region of the atmosphere to change the local weather. For example, heating the air could raise its temperature above the

dew point, which could disperse fog or clouds. This would allow surveillance systems to see previously obscured ground targets. Other effects could include creating local storms or winds, and grounding enemy aircraft.

Operational Enhancement. Weather has always been a dominant factor in military operations and any ability to control it would give significant military capability.

Key Enabling Technologies. Extremely high power DE systems would be required to be able to heat a large volume of air quickly enough to affect the weather. The laser wavelength would have to be chosen to be strongly absorbed in the correct type of air. For example, hydrogen fluoride lasers operate at 2.7 microns, a wavelength that is strongly absorbed by water vapor. Laser beams from carbon dioxide lasers operating in the region of 10.6 microns are attenuated by atmospheric carbon dioxide. Numerous other technological breakthroughs would have to take place in energy sources, large optics, and modeling of nonlinear dynamics before this concept could be given serious consideration.

Challenges. The required power levels are so high that this idea must await multiple breakthroughs in laser technology. Further, weather is inherently nonlinear and any attempt to manipulate it may cause adverse unintended consequences. Careful, validated modeling should be undertaken before any field tests are considered. Finally, international agreements may restrict weather modification technology.

Scoring.

Technical feasibility: 1. Technical maturity: 1. Operational enhancement: 5. Cost: 1. Total Score: 8.

Summary of Concept Scores

Table 5 summarizes the scores of the 28 concepts that were examined in this section. Not surprisingly, the highest ranked concepts tend to be those that augment other systems or build on existing technology. The top concepts are listed here in order of total score (shown in parentheses):

- Laser communication and data relay (17)
- Target designation (16)
- Alignment and docking guidance systems (16)
- Deep space laser altimeter (16)
- Remote sensing for battle damage assessment (16)
- Battlefield illumination (15)
- Satellite-to-satellite Doppler velocimeter (15)
- Weather monitoring and characterization (15)
- GBL ASAT (15)
- Environmental remote sensing (14)
- SBL ASAT weapon (13)

The top concept, space-based laser communication, is maturing in the commercial sector as well as within NASA and DOD. It needs no further elaboration but should continue to be pursued in a coordinated manner. In the subsequent sections, the SB-LTD and SB-BI

concepts are discussed in more detail as they are militarily unique applications.

Table 5. Composite Scores for Concepts

Concept	Feasibility	Maturity	Enhancement	Cost	Score
ENALBING SYSTEMS					
target designation	4	4	5	3	16
battlefield illumination	4	3	5	3	15
guidance (alignment, docking)	5	4	2	5	16
deep space laser altimeter	5	5	2	4	16
satellite-to-satellite Doppler velocimeter	4	4	2	5	15
INFORMATION GATHERING SYSTEMS					
remote sensing for BDA	4	4	5	3	16
environmental monitoring	4	3	4	3	14
weather monitoring and characterization	4	3	4	3	14
space derbis cataloging	3	3	4	2	12
Integrated Tactical Warning/Attack Assessment	2	2	3	2	9
active illuminator/imager for space surveillance	3	3	3	3	12
INFORMATION RELAYING SYSTEMS					
sensor pointing accuracy beacon network	4	2	2	3	11
satellite traffic management VIFF	4	1	1	5	11
laser communication and date relay	5	5	5	2	17
space track accuracy improvement	3	2	3	2	10
space-based reference grid	3	2	3	2	10
holographic projector	1	1	5	1	8
ENERGY DELIVERY SYSTEMS					
laser rocket propulsion	2	2	3	2	9
power beaming (earth to space)	2	2	3	2	9
power beaming (space to earth, space to space)	2	2	4	2	10
space derbis clearing	3	2	5	1	12
space-based counterforce weapon	3	2	5	1	11
space-based BMD weapon	3	3	5	1	11
GBL ASAT weapon	4	4	5	2	15
space-based ASAT weapon	4	4	5	2	13
space-based counter-air weapon	3	3	5	1	12
planetary defense weapon	2	1	1	1	5
weather modification system	1	1	5	1	8

VIII. SPACE-BASED LASER TARGET

DESIGNATORS

As described earlier, enabling systems enhance the capability of existing systems. Because they are not adding a new capability, the concepts should be assessed in terms of the potential improvement in operational effectiveness. Existing enabling laser systems include laser range finders (LRF) and laser target designators (LTD), which have become indispensable on the modern battlefield, and laser illuminators that augment night vision devices. The illuminators are just entering the operational forces. In this section, the space-based laser target designator concept is examined in more detail as one that could be fielded rapidly.

As the military looks to the new century, precision engagement has emerged as one of the central tenets. According to *Joint Vision 2010*, precision engagement actually refers to a "system of systems" that incorporates intelligence, surveillance and reconnaissance (ISR) systems to locate and identify the targets, improved command and control (C2) systems to commit forces to attack the target, enhanced munitions systems to deliver highly accurate lethal forces against the target, and refined battle damage assessment (BDA) technologies to evaluate the strike and permit rapid re-engagement if necessary.[126] Thus, precision engagement is truly an operational concept, not just a tactical manuever. The Air Force offers a strong capability to execute this concept and has incorporated *precision engagement* as one of its six core competencies.

One of the challenges facing the United States in the new era of warfare is to rapidly project power from long distances. The US has fewer overseas bases from which to launch sorties. Also, there are increasing problems in obtaining basing rights and overflight approvals from other countries on short notice. Thus, when a situation arises where the US needs to rapidly project lethal power against an adversary, a capability for long-range precision strike would be invaluable.

An intriguing aspect of PGMs is the concept of nonlinear operations.[127] This term refers to the fact that a small "force" can create an unexpectedly large "reaction"—one bomb can have much greater lethality due to the increased accuracy and thus increase the utility of the weapon system. For example, in the Gulf War, only 4.3 percent of the bombs dropped on the Iraqi forces were laser-guided bombs (LGB) yet they caused about 75 percent of the serious damage to strategic and operational targets.[128] The ability to hit a target precisely where it is most vulnerable is at the heart of the nonlinear aspect of PGMs.

Linking precision with effectiveness is not a new concept. Every warrior has had a pressing need for more accuracy in delivering lethal force to the intended target. Technology has provided many solutions, including the development of the theory of ballistics, new weapons such as the rifle, and high-tech devices such as the Norden bomb sight. However, the last half of the twentieth century has seen a tremendous improvement in the precision with which lethal force can be delivered. While 108 B-17's dropped 648 bombs to obtain a 96 percent chance of hitting a power plant in World War II, it only took a single aircraft with two LGBs during the Gulf War to achieve the same result.[129]

Laser target designators provide enhanced aimpoints for laser guided weapons (LGW) to use as it guides itself to the target. The concept of using space-based LTDs (SB-LTD)

occurred in both the *Laser Mission Study*[130] and the *New World Vistas* study.[131] The munitions may be LGBs that fall under the influence of gravity or laser guided missiles (LGM) such as the Maverick missiles that use rocket motors to increase their range. (Some Mavericks are laser-guided; others use other sensing techniques to guide to the target.) The operational enhancement and the success of LGWs has been clearly demonstrated since the first use against targets in North Vietnam such as the Thanh Hoa and Paul Doumer bridges,[132] and most recently in the Gulf War.

All the LTDs in use are based on the Nd:YAG laser operating at 1.06 microns, a wavelength that propagates very well through the atmosphere. The output is emitted in very short pulses on the order of 10 nanoseconds in duration and may be encoded by a pulse code modulation (PCM) scheme to reduce the risk of jamming or spoofing the LGW.[133] The laser light scatters off the target and the electro-optical (EO) sensor on the weapon captures it, computes any necessary flight path corrections, and sends the control signals to flight surfaces to place the weapon on target. From a conceptual point of view, the final "target" of the LTD is not the target slated for destruction, but rather the EO sensor on the munition. This distinction highlights the need to have the munition in the zone of sufficient scattered radiation so it can acquire the aimpoint.

The technical requirements for a space-based laser designator would be to acquire the desired target and then place the laser beam on the target from orbit at the right time for a LGM to lock on the beam and impact the target. The concept is best understood by breaking it into sequential functions, as shown in the following figure.

Figure 5. Operational Concept for Space-Based Laser Target Designation

Acquiring the target is the first step and typically involves a human in the loop. Due to operational constraints of the application of deadly force, the "man-in-the-loop" is expected to continue. Thus, an optical system would be required with sufficient resolution to image the target and then relay that image to an operator who is either on or near the earth's surface. One key advantage of the space-based systems is that the operator does not need to be near the target zone.

The target acquisition, pointing, and tracking (APT) problem is a particularly challenging aspect of space-based LTDs. Highly stabilized platforms will be required. Fortunately, recent experiments under AF Phillips Laboratory sponsorship have successfully demonstrated a pointing system known as the Inertial Pseudo Star Reference Unit (IPSRU) that achieved less than 40 nanoradians of total jitter.[134] This is equivalent to holding a crosshair on a target the size of a quarter (about two cm or one inch in diameter) at a range of 500 km or 270 NM.

See Graphic.

Once the operator identifies and locks onto the target through the imaging system, the laser beam would be generated on the satellite. The laser would be a medium power, Nd:YAG laser operating at 1.06 microns in a pulsed mode. The laser would likely be powered by high efficiency diode lasers or pumped by solar energy. The output would be appropriately coded to match the LGW. The output optics would need to be sufficiently large to make the spot on the target fairly small. However, since the LGW detects scattered light and tracks to

the centroid of the laser spot, the spot may need to be only a few meters in diameter for some targets. Using a first order calculation based on diffraction limited propagation, a 1.06 micron beam emitted by a one meter diameter telescope and focused on a target over a range of about 370 km generates a spot of about one meter in diameter.[135] Even allowing for spot size growth due to the actual optical system and propagation effects such as scintillation, a spot of a few meters in diameter could be generated from LEO using an output optical diameter of about one meter. A typical laser designator has a beam divergence of about 0.5 milliradians, generating a spot of about 4.5 meters at a range of five nautical miles. Thus, the SB-LTD could approximate current LTD performance.

The use of precision guided munitions is the essence of the AF core competency of *precision engagement*, and space-based laser target designation has tremendous potential for enhancing this capability. The ability to designate targets from space means any point on the globe can be attacked using stand-off weapons released far from the target. Further, SB-LTDs have the potential of attacking mobile targets or providing intermediate guidance points when coupled with laser guided missiles.

Another motivation behind increasing the stand-off range of LGWs is the risk to human operators during the terminal phase of the PGM delivery. Although some PGMs are autonomous, as will be discussed later, having a "man in the loop" provides a positive control in the use of deadly force. A look back at the Gulf War illustrates this point:

Cockpit video images of laser-guided bombs homing in on their targets captivated the viewing public during the Gulf War. What the public didn't know was that the launch aircraft were potentially vulnerable to enemy fighters or air defenses during that targeting process. The aircrews had to keep the video crosshairs locked on their targets to "illuminate" them with their laser designators during the relatively long flight of each bomb.[136]

Although the illumination is typically only active during the final seconds of the weapons delivery, the crew needs to be close the target and thus put at risk. In the case where the designation is coming from troops on the ground, the risk may be even greater because they are less mobile and cannot leave the target area rapidly.

A variety of technologies are crucial to the SB-LTD concept. High-data-rate communications links are required to transmit real-time images of the target area to the human controller who would be based in a ground or airborne command and control center. Moderately large (meter diameter), lightweight optics would be required for both the imaging and the laser systems. Ultraprecise tracking platforms would be required to permit stable imaging of the target while the LEO satellite moves quickly overhead. Medium power Nd:YAG systems generating over 10 joules per pulse would likely be required, although a detailed energy analysis has not been done here. This is not an overly challenging requirement and could be achieved by current technology. Current military LTD lasers generate about 160 mJ per pulse or less.

In order to implement an operationally effective SB-LTD system for general military use, a number of expensive LEO satellites and controller stations would be required. A system that would provide limited capability for ultra-precise, low-risk strikes would not require an extensive system. Also, human control of target designation will prove challenging due to

the limited target resolution at long distances and the high speeds of the satellites. Finally, exceptional intelligence is needed to identify where the targets are.

IX. SPACE-BASED BATTLEFIELD ILLUMINATION

Space-based battlefield illumination is an 'enabling system' concept that is at the stage where it could be rapidly developed and fielded, improving multiple operational systems. Being able to see targets has always been crucial to military effectiveness and a number of electro-optical systems like NVDs and FLIRs have been fielded to give the warfighter the ability to see targets in adverse conditions. Further, some surveillance and reconnaissance systems examine targets in the visible and infrared regions. Laser illumination can augment all of these systems.

Active Illumination

One of the revolutionary technologies used by the US military is low light level imaging systems. Examples include the starlight scopes and night vision devices (NVD) that use image intensifiers that amplify visible and near infrared light (typically in the wavelength region of 0.4 to 0.9 microns) to create an image bright enough to be seen and FLIR systems that use cooled far infrared detectors (such as mercury cadmium telluride (Hg:Cd:Te) detectors operating in the 8 to 12 micron region) to image the heat emitted by objects. Other systems, such as imaging reconnaissance satellites, presumably use very sensitive detectors to gather passively the reflected and emitted light from the target of interest in order to create the image. These systems have high gain to amplify the very weak EM radiation that enters the system. There still have to be some photons to be detected.

Using spotlights to illuminate targets was used as long ago as World War II for detecting German aircraft on night bombing missions over London. Recently lasers have been used as illuminators for NVD with the advantage that the narrow wavelength of the infrared laser can not be seen by the unaided eye, retaining the covertness desired in night operations. Typically the laser is a gallium-arsenide (GaAs) semiconductor laser operating in the 830 nm region. Laser illuminators include small handheld laser pointers like the Long Range Laser Pointer (LPL-30)[137], rifle-mounted systems like the Havis M16 aiming light[138] and even new systems like the GLINT illuminator on the AC-130U gunship.[139] If illuminators can be used in these modes, why not use them from space?

The concept is to project a laser beam from orbit to flood a broad region (the battlefield) with additional photons of the wavelength that can be detected by the system that is being enhanced. The concept was included in the *Laser Mission Study*[140] and *New World Vistas*[141] Simply increasing the ambient light should improve detectability because the sensor will be operating in a more efficient region of its response. Considering the two systems of most interest to be NVDs and FLIRs, GaAs and CO_2 lasers would be the best candidates for battlefield illuminators.

Improving the ability to detect targets while reducing the adversary's ability to detect you has obvious military advantages. However, whenever a system is emitting any form of EM radiation, it risks detection if an adversary is looking in the right spectral region. Using a secondary source, such as a space-based laser illuminator, reduces the risk because the

source is not collocated with the friendly observer. Thus, the military enhancement of the concept of space-based battlefield illumination has good operational enhancement.

This concept relies on accurate pointing of a laser at the surface of the earth. Thus, highly accurate ephemeris on the satellite's location is required, available through GPS and ground-station updates. The IPSRU unit described earlier can provide the pointing accuracy. The laser system needs to be powerful enough to increase the illumination on the ground to a level that enhances imaging.

As a first order estimate of the order of magnitude power requirements, the object is modeled as if it were emitting EM radiation as a greybody of a certain temperature but the radiation is actually scattering off from the object by the battlefield illuminator. The Planck Radiation Law for a greybody is derived from fundamental laws of physics and provides the spectral radiant exitance, M_λ, which is the emitted power per surface area of the object:

or, substituting in the value of the constants, using wavelength in microns, and converting units so the result is in W/cm^2-µm,

Here, e is the emissivity of the object, modeling how close to an ideal blackbody radiator the object is. It takes values between 0 and 1. For this example, the emissivity is set to 0.4. If the temperature of the greybody is set at 300K (27⊃C or about 80⊃F, which roughly correlates to the skin temperature of humans), the spectral distribution appears as shown in Figure 6. (By considering a typical temperature for detectable objects in a nighttime environment, this simple model avoids discussing the specific detectibility (D*) of fielded imaging systems.) Objects at this temperature have a peak emission in the 8 to 12 micron 'window' of good atmospheric transmission that is detected by most FLIR systems. Integrating the emission in that spectral range, the object emits about 5 mW/cm^2. Thus, the battlefield illuminator would have to provide approximately that fluence over the illuminated area to make objects at background temperature stand out to FLIR systems.

Figure 6. Greybody Exitance Curve for 300 K Object.

If we want every square centimeter to be scattering that amount of power over the area of a football field (roughly 30 meters by 100 meters), and assuming a homogenous scattering surface, this equates to 150 kilowatts. Assuming a factor of three loss in the atmosphere, we would need approximately a 450 kilowatt laser on the space platform. This is a very large laser that might be achievable with some advances in CO_2 laser technology. It exceeds the foreseeable future scaling of semiconductor lasers, although shifting to the shorter wavelength improves the signal-to-noise ratio and using a smaller illumination spot would reduce the power requirements substantially. Finally, it is important to note that the laser need not be a coherent illuminator, so multiple lasers, each operating incoherently with respect to the others, could be combined as the illumination source.

See Graphic.

Challenges

The most significant technical challenge in this concept is developing a sufficiently powerful, space-qualified laser. The output aperture does not have to be as large because

the spot size on the ground (and thus the desired beam divergence) is not small. For a SB-BI positioned at 200 NM, a 170 microradian divergence is required to make a spot about 60 meters in diameter. Using the approximate relation for divergence of $\phi \sim \lambda/D$, the diameter of the output beam would have to be at least 6 centimeters. Because that is too small to take the high power output, the output beam would likely be transmitted through a telescope that was defocused.

Operationally, a small constellation of these illumination satellites would be required in order to give suitable coverage. The cost of the system would be fairly high, but the command and control systems would be less complex than the SB-LTD because the illuminator is equivalent to a laser spotlight and should pose an insignificant safety hazard.

X. MOVING CONCEPTS INTO THE FIELD

When a military conflict arises, there is no time to develop new weapon systems. The tools that in the inventory are the ones that must be used. As Colonel John Warden wrote, the commander must face the fact that "everything must be built around the reality of his forces, not on how he would like them to be."[142] The constant challenge is how to rapidly move new warfighting technologies from an initial concept to hardware in the field. During World War II, new aircraft designs could reach production in a few years, under the intense pressure of the war. The shortened 'cycle time' for moving technology into the field is also illustrated by a vignette on electronic warfare:

In the Pacific the Japanese used radar as an aid to their torpedo bombers in the Battle of Leyte Gulf. When it was discovered that the frequency of the Japanese radar sets was below the lowest frequency of the high-power magnetron jammers then used to screen the American fleet, a call for aid went back to the scientists at the laboratory at General Electric. After a week of furious experimentation and activity, the laboratory delivered fifty new tubes. When jamming was again turned on, the Japanese bombers on the radar scopes could be seen to waver, turn away, and finally turn back.[143]

Similar success stories can be told about the 28-day development of GBU-28 'bunker buster' bombs by AF's Wright Laboratory during the Persian Gulf War[144] and the field tests of Saber 203 laser illuminators by the Phillips Laboratory during the Somalia troop withdrawals.[145] In all of these cases, existing technology was put together in new packages or altered to function in new ways and then quickly prototyped for field units. The risk of the equipment not functioning properly was high, but the potential payoff was worth the risk.

Today, fielding new weapon systems may take a decade or more. The problem of transitioning technology has become more difficult as the costs have risen significantly and the technology has become more complex. Part of the reason is the demand to use the most sophisticated technology available in order to give the most capable weapons possible. The aircraft of WWII faced less intricate design and manufacturing than today's aircraft with multifunction CRT displays and composite materials. Also, the electronics of today's weapons and communications systems use ultrahigh density integrated circuits that may require unique design and manufacturing techniques, and highly complicated software that may consume hundreds of thousands of lines of computer code and take years to design and

debug. Another reason for the long cycle time is the demand to conduct extensive developmental and operational tests to ensure that the new systems are performing as specified. Yet the goal of giving the US warfighter the technology needed increases the impetus to find faster ways to field new systems. A number of acquisition reforms are underway within DOD and are more fully discussed elsewhere.[146] For example, the Air Force's "Lightning Bolt Initiative #10" is investigating ways to reduce the cycle time in getting technology developed. The focus in this section is on exploiting a few of the channels that can move some of the space-based laser concepts into the field more quickly.

The current approach to developing new technology is the Air Force Modernization Planning Process.[147] It is a complicated chain that begins by having the operational user define the requirements through a strategy-to-task analysis, that generates a Mission Area Assessment (MAA) that discusses the perceived threat, and a task-to-need analysis that results in a Mission Needs Analysis (MNA) and a Mission Area Plan (MAP), which identify technological deficiencies in accomplishing a given mission area, such as space support or information warfare. The operational community and the R&D community work together on Technical Planning Integrated Process Teams (TPIPT) where all of the participants in the development process can discuss the deficiencies and what technologies might overcome them. There are presently over 20 TPIPTs being managed by the AFMC Product Centers. The Air Force description of the TPIPTs highlights the integrated nature of the concept:

TPIPTs are responsible for identifying and addressing customer technology needs with an optimized and integrated AFMC response. The TPIPT serves as the primary interface between the MAJCOM and AFMC to ensure that the MAP and the related TMP budgets and schedules are fully integrated and mutually supporting. The TPIPTs consist of a team of users, development planners, systems engineers, scientists, logisticians, and test engineers that tap all AFMC organizations and expertise to respond to customer needs. The TPIPT provides support to the Mission Area Planning process during all phases from MAA through development of the MAP.[148]

The TPIPT members are often the middle managers who have the expertise to know what will work either operationally or technically and the freedom to be innovative. Accessing this type of group has been the key to generating new knowledge in Japanese companies, which raises a "middle-up-down" path to innovation.[149] A central idea is the empowerment of these middle managers by the senior leadership in the corporations, an issue that should be carefully considered by senior AF leadership. Thus, the TPIPT process seems well designed to bring together all the organizations that have a vested interest in developing new technology to meet operational deficiencies. Figure 7 shows the flow from user requirements to the start of the acquisition process that provides the systems to accomplish the missions identified at the first stage.

Figure 7. The Air Force Modernization Process[150]

The TPIPTs develop the Mission Needs Statement (MNS) or Operational Requirements Document (ORD) that then justify the development program to be considered for the AF Program Objective Memorandum (POM) to obtain funding and begin the development process. Because the POM process only occurs every two years, starting a new program can take several years, and then completing that program a number of additional years. The

long road to acquiring new systems is filled with challenges, and this discussion has ignored the many levels of review that occur from the Joint Requirements Oversight Council (JROC) down through the services. There ar numerous problems with the current acquisition process.[151] Buying effective and reliable high-technology weapons systems is a complicated and time-consuming if the final product is to perform under the ultimate test of battle.

See Graphic.

Many of the "lasers in space" concepts can be pursued through the normal acquisition process. The technical challenges in such concepts as power beaming, space debris clearing, and space-based laser weapons are substantial enough that an accelerated process would not result in fielding systems sooner than the normal process. The TPIPTs are the right place to integrate these concepts into the Mission Area Plans and then into the POM process. Other space-based laser concepts, such as the higher scored concepts, would benefit from a more rapid transition from the laboratory to the field. Alternative approaches to 'fast-track' concepts into demonstrations and then into fielded systems are discussed next.

ATD and ACTD Approaches

The Advanced Technology Demonstration (ATD) and Advanced Concept Technology Demonstration (ACTD) programs were designed as pre-acquisition activities to "develop, demonstrate, and evaluate emerging technologies" to accelerate the normal acquisition process.[152]

The ATDs are specifically intended to "demonstrate the feasibility and maturity of an emerging technology" which is appropriate for several of the space-based laser concepts.[153] The technologies are usually at the "6.3" stage of development, meaning that they are fairly well understood and ready for pre-prototyping. By formalizing a technology experiment into an ATD, increased priority, better protection of funding, and heightened visibility are achieved, at the cost of increased paperwork to gain approval of the ATD. The laboratories manage and execute the ATDs, which may not be tied to a specific system concept. Coordination with appropriate TPIPTs ensures the operational users' full awareness of the demonstration.

Specifically, the Space-Based Battlefield Illuminator could be developed as an ATD. A carbon dioxide laser could be integrated with an IPSRU pointing system, a prototype control system, and a telescope system to illuminate a location on an AF test range during an orbital pass. A FLIR system would be used to evaluate the performance of the SB-BI. The ground spot size would not need to be as large as an operational system, thus decreasing the required energy from the laser to achievable levels. Several incoherent CO_2 lasers could be used and combined incoherently in the output optical system. A variety of targets could be placed at the test range to study the increase in visibility attained with the SB-BI. Such a demonstration would prove the concept for multiple applications, including aircraft FLIR systems, reconnaissance systems, and NVD usage by ground troops.

The ACTDs are "designed to respond quickly to an urgent military need."[154] Usually the

technologies are more proven than in an ATD, and the goal is more focused on proving the military utility of a concept. The ACTD often leaves a limited residual capability in the hands of the warfighter. For example, the Predator ACTD is demonstrating the unmanned aerial vehicle concept in the Balkan deployment.[155] The ACTDs are more formally approved, with final approval at the OSD level by the Deputy Under-Secretary of Defense for Advanced Technology. If the concept proves itself, the acquisition process can be greatly accelerated. The ACTD is jointly managed by the operational command and the acquisition community.

The Space-Based Laser Target Designator is based on sufficiently mature technology to qualify for an ACTD. The laser device could be developed with current diode-pumped solid state Nd:YAG lasers. The output telescope is within current capabilities, and the IPSRU pointing system has been demonstrated. The integration of the hardware with an adequate control system that includes man-in-the-loop oversight of the laser firing could be achieved with a focused effort. The high payoff of increased stand-off range is the motivation behind pursuing the SB-LTD ACTD. The laser would be directed at a ground target at a test range such as White Sands Missile Range in coordination with the release of a laser-guided bomb from a high altitude aircraft. While the initial package could be flown in a Space Shuttle mission, a dedicated satellite would be more appropriate in order to leave a residual capability. The simultaneous integration of a laser guidance package on cruise missiles like the CALCM or TLAM would complete the SB-LTD ACTD for a militarily significant stand-off capability.

The ATD and ACTD approaches are becoming more entrenched, and thus more bureaucratized with documentation and approval cycles. The senior leadership needs to guard against stifling the innovation that has been successful in previous and current demonstrations. Reducing oversight would increase the risk but also increase the potential payoff for the warfighter.

"Smart Buyer" Approach

Other methods are being tried, such as being a "smart buyer" and monitoring the private sector so that some requirements can be met by buying commercial products off-the-shelf or bought with slight modification. Examples include handheld GPS units for KC-135 cockpits (pending installation of permanent receivers), commercial desktop computers, and medical technology.

Several space-based laser concepts lend themselves to the "smart buyer" approach. The deep space altimeter has already been developed by NASA and could be readily incorporated in AF vehicles. The laser communication systems have attracted substantial interest from NASA and industry and are being co-developed with the DOD. This particular concept should be pursued more aggressively.

The concepts that use space-based, active remote sensing have been demonstrated by NASA on their LITE shuttle mission and offers another area for joint NASA-DOD development. The "smart buyer" concept would drive the DOD to work closely with NASA and its commercial partners to develop DIAL systems for military applications. An ACTD for using DIAL systems for BDA could be the next logical step.

Informal Transitions

In other instances, researchers are working informally with the warfighters to build small-scale, proof-of-concept systems for the operators' evaluation. Concepts that prove viable can then be pushed through the formal acquisition process more quickly. An excellent example was the recent evaluation of laser illuminators developed by the Phillips Laboratory's Lasers and Imaging Directorate and deployed with Marines in Somalia. The real-life experience gave invaluable feedback to both the researchers who refined their design and the operators who saw the significant potential for enhancing their mission accomplishment.[156]

One possible concept that could be pursued informally is the space track accuracy improvement. By putting a GPS-augmented, LIDAR system on a shuttle mission and illuminating a variety of satellites, improvements to the existing space object catalog could be demonstrated as a side-benefit from the technology experiment, and might convince Space Command to endorse an autonomous system of LIDAR satellites.

Air Force Battlelabs

The latest effort to bring innovation into the development process is the decision at the 1996 Fall Corona Conference to create six "battlelabs" with the charter to "identify innovative ideas and to measure how well those ideas contribute to the mission of the Air Force."[157] In part, the AF battlelabs will serve similar functions as the Army's Battle Laboratories and the US Marines Warfighting Lab, evaluating new technologies and concepts of operations in operational environments and in realistic simulations.

The battlelabs will each report to an operational command. Air Combat Command will oversee the Air Expeditionary Force Battlelab, the Battle Management Battlelab, and the Unmanned Aerial Vehicle Battlelab. The Force Protection Battlelab will work for the newly formed Force Protection Group and the Information Warfare Battlelab will operate under Air Intelligence Agency's oversight. The Space Battlelab will function under Air Force Space Command. It is this battlelab that would be ideal for transitioning some of the "lasers in space" concepts into reality.

The battlelabs will only have about 20 to 25 people and a limited budget of about $3M to $5M per year. The battlelab personnel, the operational warfighters, the SPO and research laboratory personnel, and the existing TPIPTs must cooperate to exploit the opportunity for innovation that the battlelabs offer. The battlelab commander's direct line to the MAJCOM commander should accelerate high-payoff programs.

Because the Battlelabs are intended to be a test of the operational value of different innovative concepts, the Space Battlelab would be an ideal organization to advocate both the space-based laser target designator and the space-based battlefield illuminator. The SB-LTD concept should be tested in partnership with the Air Expeditionary Force Battlelab. These two concepts would have substantial military payoff if successful. Because they are based on fairly well understood technology, that success is likely if sufficient funding and manpower is committed to the project. Indeed, since the battlelabs will have the ear of the four-star MAJCOM commander, their advocacy for projects like the SB-LTD and SB-BI would be critical for attaining successful demonstrations.

Because of the critical importance of timely, accurate BDA, another concept that the Space Battlelab could advocate, in conjunction with the Air Expeditionary Force and Battle Management Battlelabs, is the use of space-based lasers for active remote sensing of target sites immediately following an attack. The project could build on NASA's successful LITE project and the probe beam aimed at a controlled target site in a military test range. Controlled releases of effluents would validate the system prior to the bombing engagement. Similarly, using remote sensing to determine winds over a target area could be demonstrated with the same system *before* the attack to improve the accuracy of the weapons.

These demonstrations would need to be done in close cooperation with the Phillips Laboratory and other appropriate groups within AFMC. The Space Battlelab's role would be as a 'operational integrator' to put together a truly integrated technology demonstration. A team of operational users, technologists, and contractors needs to be solely dedicated to these projects in order to be successful. One prevalent problem in today's acquisition arena is the overcommitment of personnel to too many different projects, leading to insufficient effort on any specific project.

It remains to be seen if any of these alternative approaches would be successful for fielding lasers in space. The ATD and ACTD processes have already produced solid results. The "smart buyer" program seems best suited for C4I systems and support systems such as medical technology. The informal process has worked on several small-scale projects but faces challenges in being institutionalized in a "rapid response SPO" so that the formal acquisition can yield quick results. The battlelabs are coming into being during the summer of 1997, at the same time as the four AF laboratories are being merged into one 'megalab' called the Air Force Research Laboratory. The pressure to be innovative continues, and all of these schemes offer potential for success.

XI. CONCLUSIONS AND RECOMMENDATIONS

The merging of the maturing laser technology with the unique environment of space offers substantial opportunities to improve the capability of the warfighter. A wide range of concepts has been discussed in this report based primarily on recent strategic planning studies. A functionally oriented taxonomy grouped the concepts to better match the warfighter's taxonomy. A scoring process allowed a rough sorting of the concepts that highlighted several that are poised for rapid implementation. A number of different mechanisms exist for moving these concepts from the drawing board to the hands of the operational forces. The various agencies involved must now make it happen.

Conclusions

The functional taxonomy sorted the concepts into four major categories: enabling systems, information-gathering systems, information-relaying systems and energy delivery systems. Equally important, this taxonomy relates directly to the warfighter's taxonomy of aerospace control, force application, force enhancement, and force support, so that the various concepts can be included in the appropriate Mission Area Plans. The new AF core competencies also are well supported by developing space-based laser systems.

Based on this report's evaluation, the most attractive concepts are laser communication systems, laser remote sensing systems for applications such as BDA, weather monitoring and environmental measurements, space-based laser target designators, space-based battlefield illumination and several variants of laser instrumentation for spacecraft. The feasibility of lasers for the ASAT mission, both from the ground and from space, is maturing and systems could be deployed if sufficient priority and resources were devoted to this mission and if international treaties did not prevent it. The vulnerability of currently fielded satellites is higher than other target sets, making this laser weapon application more near-term than other missions, such as BMD or counter-air.

The DOD and industrial laboratories must develop a number of key technologies to bring the concepts to fruition. More powerful and efficient lasers with better beam characteristics, such as wavelength tunability and improved temporal modulation, are central to concepts such as the active remote sensing and weather characterization. Engineers must integrate advanced acquisition, pointing and tracking systems with lasers to develop a number of applications, such as the SB-LTD and HEL weapons. Also, highly automated command and control systems are needed, with on-board data fusion offering the advantage of reducing data rates, crucial to the success of several concepts like remote sensing and laser target designation.

The best operational concepts are those that increase the situational awareness of the warfighter and the ability to direct force against intended targets. The remote sensing concepts and laser communication systems aid the situational awareness, while the SB-LTD, SB-BI and remote sensing of wind speed aid the second purpose. While speed-of-light weapons would be ideal for the emerging "if you can be seen, you can be killed" warfare of the next century, the space-based laser technology is still many years away from effectively achieving that goal, except for limited applications. Ground-based weapons for missile defense and ASAT operations could be fielded sooner and the Airborne Laser aircraft (having even received the AF designation of YAL-1A) should put photons on target early in the next decade. Thus, the operational enhancement of lasers in space is firmly established.

Recommendations

In particular, laser communication systems and laser remote sensing systems have already been demonstrated and should be aggressively integrated into next generation spacecraft via ACTD and "smart buyer" approaches. The SB-BI concept is well suited for a ATD experiment on a future Space Shuttle mission. The SB-LTD concept would make an excellent ACTD and a high payoff project for the newly formed Space Battlelab. The requisite subsystems for these demonstrations either exist or are within reach. What is required is some effort to develop the concepts into a viable program plan and market it. The Space Battlelab should be actively engaged with one or two space-based laser concepts as quick-payoff items to demonstrate relevant innovation.

Improved coordination and contact within the R&D community and between the R&D and operational organizations are critical for efficiently moving forward on lasers in space. The AF and NASA are both developing space-based laser concepts, and, in some (but not all) cases, are working on coordinated projects. However, there would be great value in a

periodic workshop of DOD and NASA program managers who are working with space-based laser systems to discuss results and problems. Such conferences should be sponsored by the major organizations like the Phillips Laboratory and NASA Langley rather than arising out of the working level. Similarly, the communication between the R&D community and the operational users should be improved by regular conferences where the focus is on workshops and group discussions, instead of lengthy, one-sided presentations in darkened rooms.

The opportunity is at hand to develop and deploy lasers in space to meet a variety of the warfighter's needs. Diligence, commitment and vision are needed to make this opportunity a reality.

ACRONYMS, ABBREVIATIONS AND SYMBOLS

The following acronyms and terms are defined for the convenience of the reader.

λ wavelength

μm microns, 0.000001 or 10^{-6} meters

ABL Airborne Laser

ABM Anti-Ballistic Missile

ACSC Air Command and Staff College

ACTD Advanced Concept Technology Demonstration

AFMC Air Force Materiel Command

AFSPC Air Force Space Command

ALI Alpha/LAMP Integration

ALL Airborne Laser Laboratory, a modified C-135 with a large CO_2 laser

AM Amplitude Modulation

APT Acquisition, Pointing and Tracking

ASAT Anti-Satellite

AU Air University

AWACS Airborne Warning and Control System

AWC Air War College

BDA Battle Damage Assessment

BMD Ballistic Missile Defense

BMDO Ballistic Missile Defense Office

C2 Command and Control

C4I Command, Control, Communications, Computers and Intelligence

CALCM Conventional Air-Launched Cruise Missile

CCD Charge Coupled Device

COIL Chemical Oxygen Iodine Laser

CO2 Carbon Dioxide

CONUS Continental United States

CPB Charged Particle Beam

CSAF Chief of Staff, United States Air Force

DEW Directed Energy Weapon

DF Deuterium Fluoride

DIAL Differential Absorption LIDAR

DOD Department of Defense

DOE Department of Energy

DMSP Defense Meteorological Support Program

DSP Defense Support Program

DUSD(Space) Deputy Under Secretary of Defense for Space

EM Electromagnetic, Electromagnetism

FLIR Forward Looking Infrared System

FM Frequency Modulation

GaAs Gallium Arsenide

GBL Ground Based Laser (usually referring to a weapon class device)

GEO Geosynchronous Earth Orbit

GPOW Global Precision Optical Weapon

GPS Global Positioning System

HEL High-energy Laser

He-Ne Helium-Neon

HF Hydrogen Fluoride

HPM High Power Microwave

ICBM Intercontinental Ballistic Missile

IFF Identification Friend or Foe

IPSRU Inertial Pseudo Star Reference Unit

IRCM Infrared Countermeasures

ITW/AA Integrated Tactical Warning/Attack Assessment

JROC Joint Requirements Oversight Council

LADAR Laser Detection and Ranging

LAMP Large Advanced Mirror Program

LANTIRN Low Altitude Navigation and Targeting Infrared System for Night

Laser Light Amplification through Stimulated Emission of Radiation

LEO Low Earth Orbit

LGB Laser Guided Bomb

LGM Laser Guided Missile

LGW Laser Guided Weapon

LIDAR Light Detection and Ranging

LITE Laser In-space Technology Experiment

LMS Laser Mission Study

LODE Large Optics Demonstration Program

LPD Low Probability of Detection

LPI Low Probability of Intercept

LRF Laser Range Finder

LTD Laser Target Designator

MAA Mission Area Assessment

MAP Mission Area Plan

MEO Middle Earth Orbit

MILES Multiple Integrated Laser Engagement System

MIRACL Mid-Infrared Advanced Chemical Laser

MNA Mission Needs Analysis

MNS Mission Needs Statement

MOOTW Military Operations Other Than War

MOPA Master Oscillator - Power Amplifier

MSI Multi-Spectral Imaging

NASA National Aeronautics and Space Administration

Nd:YAG Neodymium:Yttrium Aluminum Garnet

NM nautical miles (equal to 1852 meters)

nm nanometers (10^{-9} m)

NRT Near-Real-Time

NVD Night Vision Devices

ORD Operational Requirements Document

PAVE Precision Avionics Vectoring Equipment

PCM Pulse Code Modulation

PGM Precision Guided Munitions

PME Professional Military Education

POM Program Objective Memorandum

PSYOP Psychological Operations

R&D Research and Development

RADAR Radio Detection and Ranging

SAB Scientific Advisory Board

SBL Space Based Laser (usually referring to a weapon class device)

SB-BI Space-Based Battlefield Illuminator

SB-LTD Space-Based Laser Target Designator

SDI Strategic Defense Initiative

SDIO Strategic Defense Initiative Organization

SNR Signal to Noise Ratio

SOR Starfire Optical Range, located at Kirtland AFB, NM

TACAN Tactical Air Navigation

TEL Transporter Erector Launcher

TLAM Tomahawk Land-Attack Missile

TMD Theater Missile Defense

TMP Technology Master Process

TPIPT Technical Planning Integrated Product Team

UAV Unmanned Aerial Vehicle, a.k.a. Uninhabited Aerial Vehicle

URL Uniform Resource Locator (addresses for World Wide Web sites)

USAF United States Air Force

VOR Very High Frequency Omnidirectional Range

Useful Terms

laser. Any of several devices that convert incident electromagnetic radiation of mixed frequencies to one or more discrete frequencies of highly amplified and coherent visible radiation.

microwave. Any electromagnetic radiation having a wavelength in the approximate range from one millimeter to one meter, the region between infrared and shortwave radio wavelengths.

radar. A method of detecting distant objects and determining their position, velocity, or other characteristics by analysis of very high frequency radio waves reflected from their surfaces.

satellite. Any object, manmade or natural, that orbits around another more massive body due to the attraction of gravity.

Notes

1. General Ronald R. Fogleman, "Strategic Vision and Core Competencies," Speech to Air Force Association Symposium, Los Angeles, CA, 18 October 96.

2. William P. Snyder, "Strategy: Defining It, Understanding It, and Making It," *Air War College Strategy, Doctrine and Air Power Reader,* Vol 1, 1997, 1.

3. A comprehensive treatment of space, including history of the early space program, a discussion of space law, and descriptions of military space systems, is contained in the two volume *Space Handbook*, by Major Michael J. Muolo, Air University Report AU-18, Air University Press, December 1993. The second volume contains useful background information on the space environment, orbital dynamics, launch systems and directed energy systems including lasers.

4. A number of articles on Corona have recently been published, including Stuart F. Brown, "America's First Eyes in Space," *Popular Science*, February, 1996, 42-47; F. Dow Smith, "The Eyes of Corona," *Optics and Photonics News*, October 1995, 34-39; Seth Shulman, "Code Name: Corona," *Technology Review*, October 1996, 22-32; Dino A. Brugioni, "The Art and Science of Photoreconnaissance," *Scientific American*, March 1996, 78-85.

5. Ralph K. Bennett, "Defenseless Against Missile Terror," *Reader's Digest*, October 1996, 102-106.

6. William M. Arkin, "Vienna meeting sets ban on blinding laser weapons," *Laser Focus World*, December 1995, 62-64.

7. The author has a PhD in laser optics and has spent the past eighteen years involved with laser applications in the US Air Force. Much of this report's discussion on the technical aspects of lasers is based on this experience with supporting references as required.

8. "Air Force awards attack laser contract," Air Force News Service release, 13 November 1996.

9. *Air War - Vietnam* (New York: ARNO Press, 1978), 79-83.

10. Kenneth A. Myers and Job G. Tockston, "Real Tenets of Military Space Doctrine," *Airpower Journal*, Winter 1988, 54-68.

11. Air Force Space Command Overview, "Where We Operate," *Guardian,* Special Edition, 5.

12. Myers and Tockston, 59.

13. Major Michael J. Muolo, *Space Handbook*, Vol 2, Air University Report AU-18, Air University Press, December 1993, 4-5.

14. Myers and Tockston, 59.

15. Because there is some matter even in deep space, there is absorption and scattering of the EM radiation that depends on the wavelength. Astronomical spectroscopy of gaseous nebula depends on these effects.

16. Muolo, Volume 2, 13.

17. Muolo, Volume 2, 14.

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33. Hecht, 190.

34. Private discussions with Lt Col Marc Hallada, Laser Devices Division Chief, Phillips Laboratory, Kirtland AFB, NM on 19 February 1997.

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36. Ray Nelson, "Reinventing the telescope," *Popular Science*, January 1995, 57.

37. This is strictly true for any EM beam that has finite transverse extent, as all real beams must.

38. Fogleman.

39. Ibid., 3.

40. Ibid., 3.

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46. Benedict et al., 6.

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54. *New World Vistas*, Directed Energy volume, x, 29.

55. *New World Vistas*, Directed Energy volume, v, 30.

56. *Laser Mission Study*, 47-48.

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58. *New World Vistas*, Directed Energy volume, x.

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63. Ibid., 25.

64. Ibid., 26.

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66. Norman P. Barnes, "Lidar systems shed light on environmental studies," *Laser Focus World*, April 1995, 87-94.

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68. Stephen G. Anderson, "Space LIDAR Shows California Haze," *Laser Focus World*, September 1995, 32, 34.

69. This graphic was obtained from URL "arbs8.larc.nasa.gov/LITE/lite_cartoon.gif" on 3 Dec 96.

70. *Laser Mission Study*, 47.

71. *New World Vistas*, Space Technology volume, 9.

72. *New World Vistas*, Sensors volume, x, 30, 33, 36, 87-89.

73. *New World Vistas*, Space Technology volume, 48.

74. *New World Vistas*, Sensors volume, 88-89.

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77. *New World Vistas*, Sensors volume, 88.

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81. *Laser Mission Study*, 54.

82. *New World Vistas*, Space Technology volume, 9.

83. *New World Vistas*, Directed Energy volume, 11.

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88. Scott Bloom and Eric Korevaar, "Fiber-Free: Laser Communications Soar to 'Unheard of' Heights," *Photonics Spectra*, February 1997, 115-120.

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127. The precise mathematical meaning of nonlinearity is unfortunately not followed in the military literature. A linear system is characterized by a linear connection between input and output, e.g., doubling an input generates twice the output. A nonlinear system is any system that deviates from this relationship. In the military concept, there is a 'historical' expectation of lethality and accuracy based on the use of "dumb" munitions and the PGMs deviate from this expectation, hence the association with nonlinearity.

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137. Ruhlman, 16. Also see *Laser Range Safety*, Military Handbook 828, 15 April 1993, A-4.

138. *Laser Range Safety*, Military Handbook 828, 15 April 1993, A-10.

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153. *Ibid*.

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155. Peter Grier, "DarkStar and Its Friends," *Air Force Magazine*, July 1996, 43.

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